

ECCOE Landsat Quarterly Calibration and Validation Report—Quarter 3, 2023

Open-File Report 2024–1017
Version 1.1, December 2024

U.S. Department of the Interior
U.S. Geological Survey

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By Md Obaidul Haque, Rajagopalan Rengarajan, Mark Lubke, Md Nahid Hasan, Ashish Shrestha, Jerad L. Shaw, Alex Denevan, Kathryn Ruslander, Esad Micijevic, Michael J. Choate, Cody Anderson, Kurt Thome, Ed Kaita, Julia Barsi, Raviv Levy, Jeff Miller, and Leibo Ding

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
nanometer (nm)	0.00000003937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)

Temperature in Kelvin (K) may be converted to degrees Celsius (°C) as follows: °C = K – 273.15.

Supplemental Information

Radiance is given in watts per square meter per steradian per micrometer (W/m² sr µm).

Within this report, quarter 1 is from January to March, quarter 2 is from April to June, quarter 3 is from July to September, and quarter 4 is from October to December. For example, quarter 3, 2023, was from July to September 2023.

Abbreviations

~	approximately
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CA	coastal/aerosol
Cal/Val	Calibration and Validation
CE90	circular error with 90-percent confidence
CNES	Centre National D'Etudes Spatiales
CPF	calibration parameter file
DOQ	digital orthophoto quadrangle
ECCOE	EROS Cal/Val Center of Excellence
EO	Earth observation
EROS	Earth Resources Observation and Science
ETM+	Enhanced Thematic Mapper Plus
GCP	ground control point
L0Ra	Level 0 Reformatted Archive
L0Rp	Level 0 Reformatted Product
L1	Level 1
L1TP	L1 Terrain Precision Correction
$L_{typical}$	typical radiance
NE Δ T	noise equivalent change in temperature
OLI	Operational Land Imager
PICS	pseudoinvariant calibration sites
RMSE	root mean square error
ROI	region of interest
SNR	signal-to-noise ratio
SPOT	Satellite Pour l'Observation de la Terre
SSM	Scene Select Mechanism
SWIR	shortwave infrared
TIRS	Thermal Infrared Sensor
USGS	U.S. Geological Survey
WRS-2	Worldwide Reference System-2

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Executive Summary

The U.S. Geological Survey Earth Resources Observation and Science Calibration and Validation (Cal/Val) Center of Excellence (ECCOE) focuses on improving the accuracy, precision, calibration, and product quality of remote-sensing data, leveraging years of multiscale optical system geometric and radiometric calibration and characterization experience. The ECCOE Landsat Cal/Val Team continually monitors the geometric and radiometric performance of active Landsat missions and makes calibration adjustments, as needed, to maintain data quality at the highest level.

This report provides observed geometric and radiometric analysis results for Landsats 7, 8, and 9 for quarter 3 (July–September) of 2023. All data used to compile the Cal/Val analysis results presented in this report are freely available from the U.S. Geological Survey EarthExplorer website: <https://earthexplorer.usgs.gov>.

This is the first quarterly report to include analysis results for Landsat 9, which was launched in September 2021. The inclusion of Landsat 9 analysis results was dependent on two factors: a complete reprocessing of the Landsat 9 data archive and enough time elapsing to begin formulating lifetime trends. In April 2023, all Landsat 9 image data acquired since the satellite’s launch were reprocessed to take advantage of calibration updates identified by the ECCOE Landsat Cal/Val Team. Additional information about the Landsat 9 reprocessing effort is available at <https://www.usgs.gov/landsat-missions/news/upcoming-reprocessing-all-landsat-9-data>.

Introduction

The U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Calibration and Validation (Cal/Val) Center of Excellence (ECCOE) focuses on improving the accuracy, precision, and quality of remote-sensing data, leveraging years of multiscale optical and thermal system geometric and radiometric calibration and characterization experience (USGS, 2021b).

This report provides observed geometric and radiometric analysis results for Landsats 7, 8, and 9 for quarter 3 (July–September) of 2023. All data used to compile the Cal/Val analysis results presented in this report are freely available from the USGS EarthExplorer website: <https://earthexplorer.usgs.gov> (USGS, 2021a).

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Background

The U.S. Department of the Interior is directed to ensure that U.S. land imaging needs are met in the future and to maintain U.S. leadership in civil land imaging and land science. Those directives come in the context of the Future of Land Imaging Interagency Working Group’s report titled “A Plan for a U.S. National Land Imaging Program” (Executive Office of the President of the United States, 2007) and two recent

¹KBR, Inc.; Work done under contract to the U.S. Geological Survey.

²U.S. Geological Survey.

³National Aeronautics and Space Administration.

⁴Science Systems and Applications, Inc.; Work done under contract to the National Aeronautics and Space Administration.

Earth observation (EO) publications (Executive Office of the President of the United States, 2014, 2016). These reports identified Landsat and other key USGS EO assets as critical components in the national EO structure, where several assets were ranked in the top 10 of more than 300 assets. Among them, Landsat ranked third or higher.

Continuity with the past is key to meeting future land imaging science needs. The Landsat program, operated by the USGS, is the longest continuous record of satellite-based Earth imaging. Landsat data quality is viewed by the remote-sensing user community as a gold standard (National Geospatial Advisory Committee, 2020).

To ensure the continued excellent quality of Landsat data, the USGS EROS Center has identified (1) maintaining a well-calibrated multidecade remote-sensing archive for science and (2) developing and understanding land remote-sensing requirements and land imaging solutions as key strategic pillars. Understanding the land imaging requirements of current and future users, along with an ability to assess the capabilities of current and future systems for meeting those requirements, is key to meeting future land imaging science needs. In the past, Cal/Val activities at the EROS Center addressing the previously mentioned pillars were spread across multiple groups. The USGS EROS Center strategically brought the multiple groups together and formed a single team in a unified project called the ECCOE to enable the USGS to more efficiently address national and global land remote-sensing needs.

Purpose and Scope

The primary purpose of this report is to provide the latest geometric and radiometric performance results for all active Landsat missions. This report provides observed geometric and radiometric analysis results for Landsats 7, 8, and 9 for quarter 3 (July–September), 2023. All data used to compile the results presented in this report are available from the USGS EarthExplorer website: <https://earthexplorer.usgs.gov> (USGS, 2021a).

Processing Level Definitions

This report frequently references Landsat processing levels. Descriptions of these processing levels are in the following subsections.

Level 0

The Level 0 Reformatted Archive (L0Ra) and Level 0 Reformatted Product (L0Rp) formats do not have sensor chip assembly or band alignment applied. L0Ra data are sensor data and spacecraft ancillary data that are reformatted for easier processing. Minor corrections to the ancillary data (such as frame number and time-code corrections) are applied, and ancillary raw data units are converted to engineering units. Image data are left in counts or digital numbers. L0Rp and

L0Ra files are in the same format, but the content is different. L0Ra files contain an entire interval of imagery, whereas L0Rp files only contain a smaller part of the L0Ra data: a Worldwide Reference System-2 (WRS-2) scene-based subset.

Level 1

The standard Level 1 (L1) image data are radiometrically and geometrically corrected. L1 Geometric Systematic Correction products are radiometrically calibrated with only systematic geometric corrections applied using the spacecraft ephemeris data. L1 Systematic Terrain Correction products are radiometrically calibrated with systematic geometric corrections applied using the spacecraft ephemeris data and digital elevation model data to correct for relief displacement. L1 Terrain Precision Correction (L1TP) products are radiometrically calibrated and orthorectified using ground control points (GCPs) and digital elevation model data to correct for relief displacement.

Level 2

The Level 2 science products are generated from L1 inputs that meet the less than 76-degree solar zenith angle constraint and include the required auxiliary data inputs to generate a scientifically viable product. Level 2 science products represent surface reflectance and surface temperature. Surface reflectance is the fraction of incoming solar radiation that is reflected from the Earth's surface. Surface reflectance product generation accounts for the temporally, spatially, and spectrally varying scattering and absorbing effects of atmospheric gases, aerosols, and water vapor, which are necessary to reliably characterize the Earth's land surface.

Surface temperature is the measurement of the temperature of the surface of the Earth in Kelvin. Provisional surface temperature is generated from the Landsat Collection 2 L1 thermal infrared bands, top of atmosphere reflectance, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Emissivity Database data, ASTER Normalized Difference Vegetation Index data, and atmospheric profiles of geopotential height, specific humidity, and air temperature extracted from reanalysis data.

Landsat Collection Definitions

This report frequently references Landsat collections. In 2016, the USGS reorganized the Landsat archive into a tiered-collection management structure. This structure ensures that all Landsat L1 products provide a consistent archive of known data quality while controlling continuous improvement of the archive and access to all data as they are acquired. The implementation of collections represents a substantial change in the management of the Landsat archive by ensuring consistent quality over time and across all instruments.

Landsat Collection 1

Landsat Collection 1 was released in 2016 and introduced collection tiers for L1 data products based on data quality and the level of processing. The tier definition purpose was to support easier identification of suitable scenes for time-series pixel-level analysis. In addition to tiered products, several changes were first introduced with the release of Collection 1 processing. Because of the release of Landsat Collection 2 in December 2020, Collection 1 processing of newly acquired data ended on January 1, 2022. Access to archived Collection 1 data products ceased on December 30, 2022. Additional information about the Collection 1 products is available at <https://www.usgs.gov/landsat-missions/landsat-collection-1>.

Landsat Collection 2

Landsat Collection 2 was released in December 2020 and marked the second major reprocessing effort on the Landsat archive (USGS, 2020a, b). Collection 2 represented several data product improvements that harnessed recent advancements in data processing, algorithm development, and data access and distribution capabilities. Additional information about the Collection 2 products is available at <https://www.usgs.gov/landsat-missions/landsat-collection-2>.

Landsat 9 Radiometric Performance Summary

The Landsat 9 on-orbit radiometric performance for this reporting quarter (quarter 3, July–September 2023) meets all requirements as outlined in USGS (2022). The quarterly Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) radiometric performance summaries are provided in [tables 1](#) and [2](#), respectively.

Landsat 9 Operational Land Imager Signal-to-Noise Ratio

The signal-to-noise ratio (SNR) for each of the OLI spectral bands is characterized at a prescribed band-specific typical radiance (L_{typical}) level, as described in [table 3](#). The SNR of a detector at a given radiance level is defined as the mean of the measured pixel radiances acquired over a homogenous target divided by their standard deviation. A curve is fit to the SNR at the measured radiance levels and is evaluated at the prescribed L_{typical} level. Before launch, the SNR was characterized at multiple stages of the instrument build, culminating in the testing of the fully integrated instrument.

Table 1. Landsat 9 Operational Land Imager radiometric performance summary, quarter 3 (July–September), 2023.

[The previous quarter is quarter 2 (April–June), 2023. OLI, Operational Land Imager; <, less than; SNR, signal-to-noise ratio; L_{typical} , typical radiance; -, not applicable; L_{high} , high radiance; RMS, root mean square; stdev, standard deviation; ≤, less than or equal to; W/m² sr μm, watt per square meter per steradian per micrometer; σ, sigma; spec, specification]

Requirement	Measured value from this quarter	Measured value from previous quarter	Required value	Unit
OLI ghosting	Meets	Meets	Varies	Percent
OLI absolute radiance uncertainty	1.9	1.9	<5	Percent
OLI absolute reflectance uncertainty	2.3	2.3	<3	Percent
OLI median SNR L_{typical}	Meets	Meets	Varies	-
OLI median SNR L_{high}	Meets	Meets	Varies	-
OLI uniformity full field of view	0.30	0.30	<0.5	Percent
OLI uniformity banding RMS	0.10	0.10	<1	Percent
OLI uniformity banding stdev	0.10	0.10	<0.25	Percent
OLI uniformity streaking	0.2	0.2	≤0.5, 1	Percent
OLI coherent noise	Meets	Meets	Less than coherent noise threshold curve	-
OLI saturation radiances	Meets	Meets	Varies	W/m ² sr μm
OLI 16-day radiometric stability	0.05	0.05	<1	Percent (2σ)
OLI 60-second radiometric stability	0.2	0.2	<0.5	Percent (2σ)
OLI inoperable detectors	0	0	<0.1	Percent
OLI out-of-spec detectors	<0.25	<0.25	<0.25	Percent

Table 2. Landsat 9 Thermal Infrared Sensor radiometric performance summary, quarter 3 (July–September), 2023.

[The previous quarter is quarter 2 (April–June), 2023. TIRS, Thermal Infrared Sensor; ~, approximately; <, less than; NEΔT, noise equivalent change in temperature; K, Kelvin; RMS, root mean square; stdev, standard deviation; -, not applicable; >, greater than; W/m² sr μm, watt per square meter per steradian per micrometer; σ, sigma; spec, specification]

Requirement	Measured value from this quarter	Measured value from previous quarter	Required value	Unit
TIRS absolute radiance uncertainty	~1	~1	<2	Percent
TIRS NEΔT (at 300 K)	0.07	0.07	<0.4	K
TIRS uniformity full field of view	0.06	0.06	<0.5	Percent
TIRS uniformity banding RMS	0.12	0.12	<0.5	Percent
TIRS uniformity banding stdev	0.06	0.06	<0.5	Percent
TIRS uniformity streaking	0.15	0.15	<0.5	Percent
TIRS coherent noise	Meets	Meets	Less than coherent noise threshold curve	-
TIRS saturation radiances	~25.0, ~23.0	~25.0, ~23.0	>20.5, >17.8	W/m ² sr μm
TIRS 40-minute radiometric stability	<0.3	<0.3	<0.7	Percent (1σ)
TIRS inoperable detectors	0	0	<0.1	Percent
TIRS out-of-spec detectors	0	0	<0.25	Percent

Table 3. Landsat 8 and 9 Operational Land Imager typical radiances for each spectral band.

[OLI, Operational Land Imager; nm, nanometer; $L_{typical}$, typical radiance; W/m² sr μm, watt per square meter per steradian per micrometer]

OLI band number	Spectral band	Center wavelength (nm)	$L_{typical}$ (W/m ² sr μm)
1	Coastal/aerosol	443	40
2	Blue	482	40
3	Green	561	30
4	Red	655	22
5	Near infrared	865	14
6	Shortwave infrared 1	1,609	4.0
7	Shortwave infrared 2	2,201	1.7
8	Panchromatic	590	23
9	Cirrus	1,373	6.0

The Landsat 9 OLI SNR is evaluated on orbit each month using onboard calibrator data and is slightly better than the Landsat 8 OLI SNR (between 3.60 and 8.72 percent band-dependent improvement). It is consistently two to three times better than requirements and about eight times better than the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) SNR. The per-band OLI median SNR at the $L_{typical}$ level (yellow bars) for September 2023, which for all bands easily exceeds the OLI SNR requirements (blue bars) by more than 50 percent, is shown in figure 1. Lifetime SNR stability at $L_{typical}$ for each OLI band is represented in figures 2, 3, 4, 5, 6, 7, 8, 9, and 10; monthly SNR values (for the detectors that have median SNRs for all bands) are denoted by the diamonds, and the uncertainties in the monthly SNR model are denoted by the error bars. The

SNR for each band has remained stable over time (within the uncertainty of the models and much greater than the required levels). Radiometric updates implemented during the Landsat 9 data archive reprocessing effort resulted in slight per-band improvement in the Landsat 9 OLI SNR (between 0.03 and 3.84 percent).

Landsat 9 Thermal Infrared Sensor Noise Performance

Noise can be defined as variation in detected signal over time when observing a stable source of radiation. For thermal sensors, noise is usually expressed in terms of a change

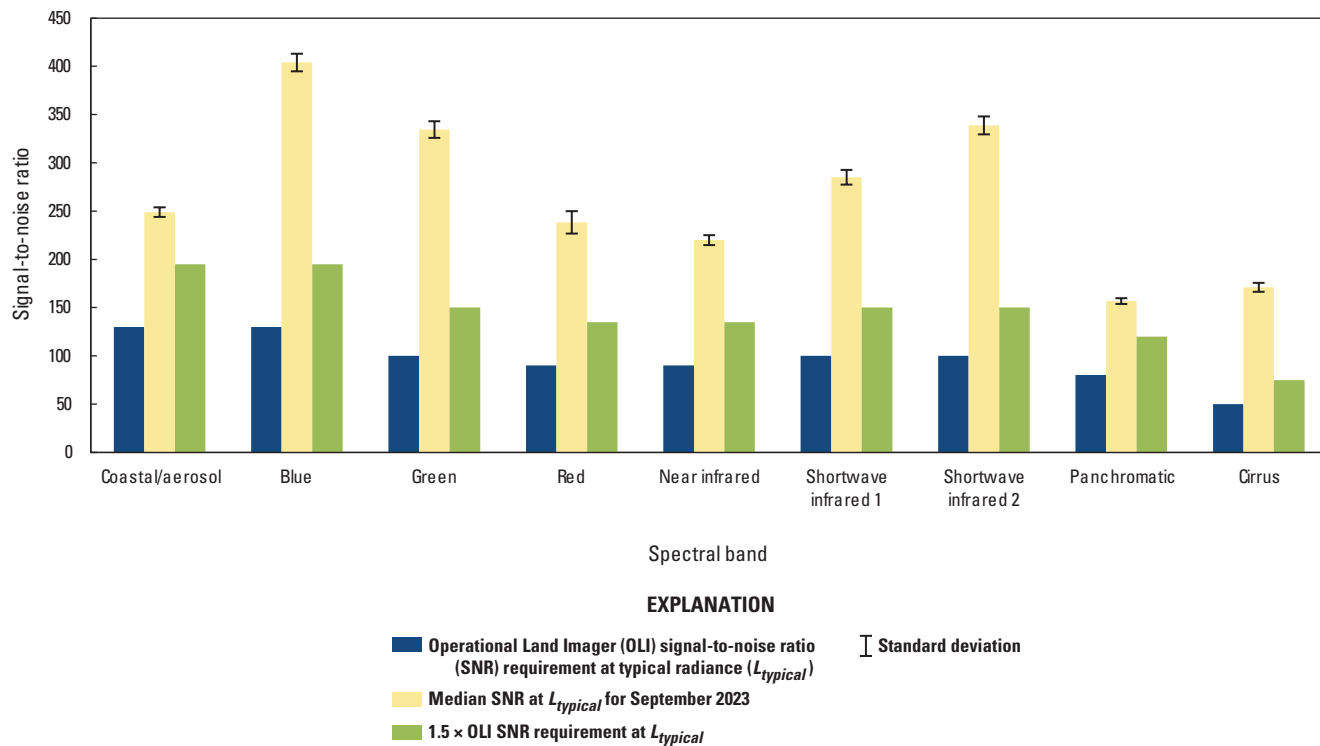


Figure 1. Landsat 9 Operational Land Imager signal-to-noise ratio performance, September 2023.

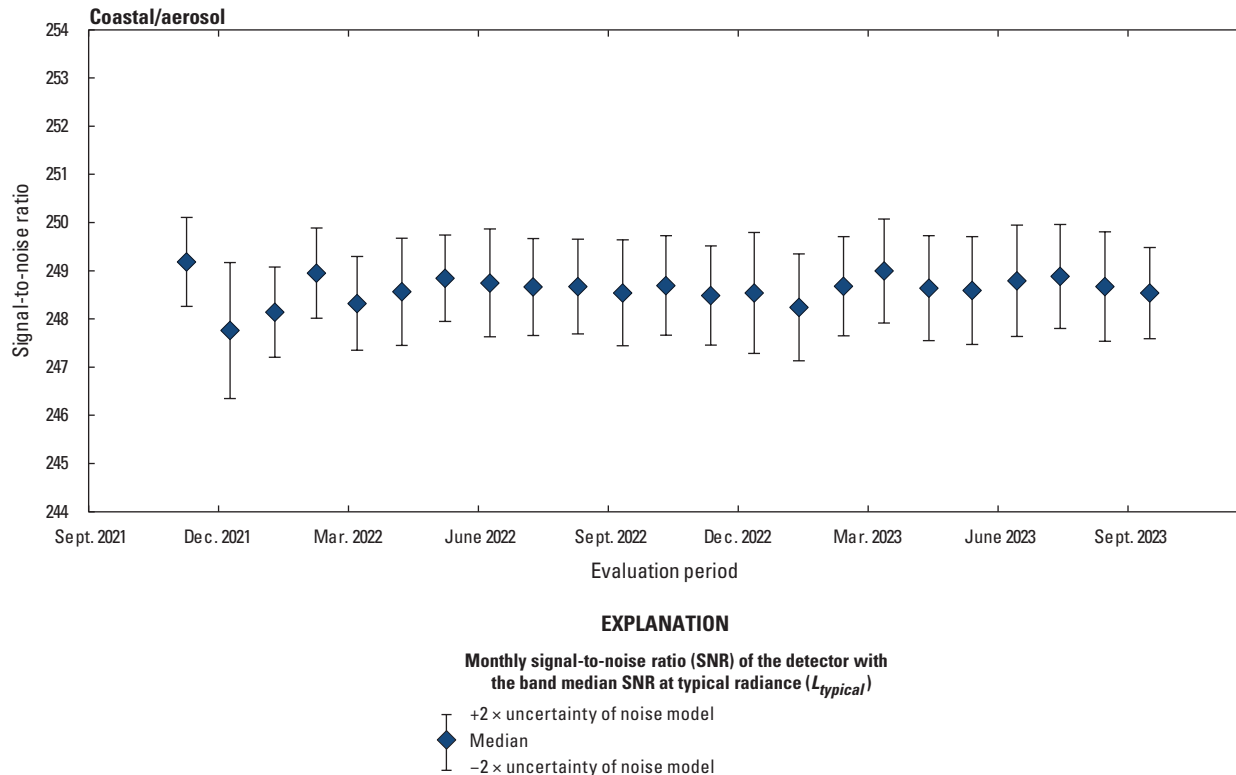


Figure 2. Landsat 9 Operational Land Imager coastal/aerosol band lifetime signal-to-noise ratio stability.

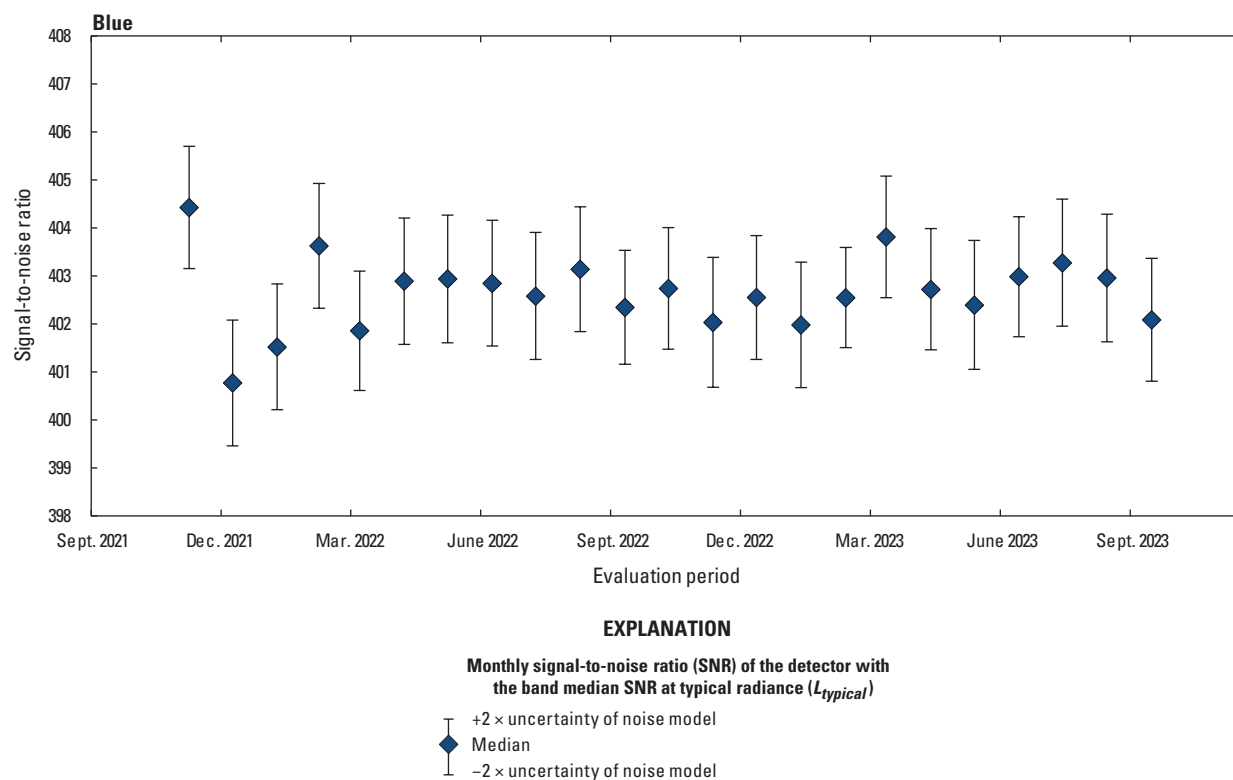


Figure 3. Landsat 9 Operational Land Imager blue band lifetime signal-to-noise ratio stability.

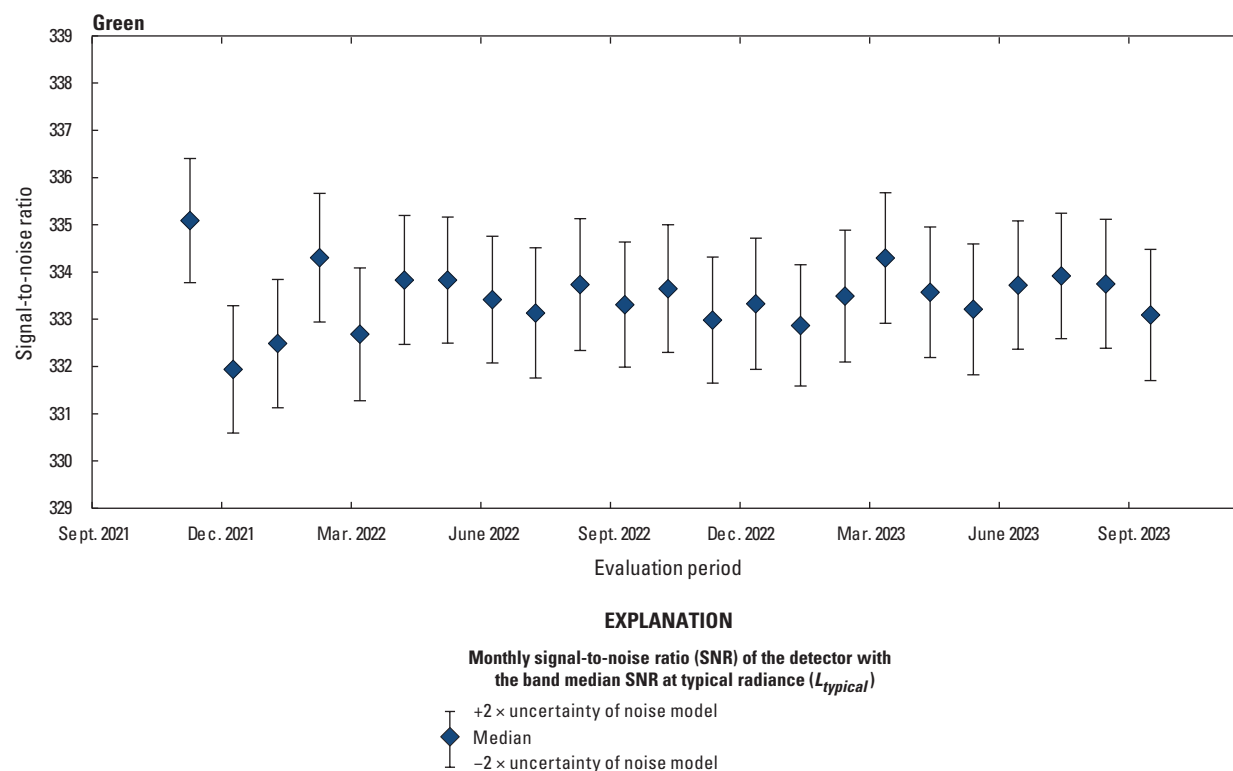


Figure 4. Landsat 9 Operational Land Imager green band lifetime signal-to-noise ratio stability.

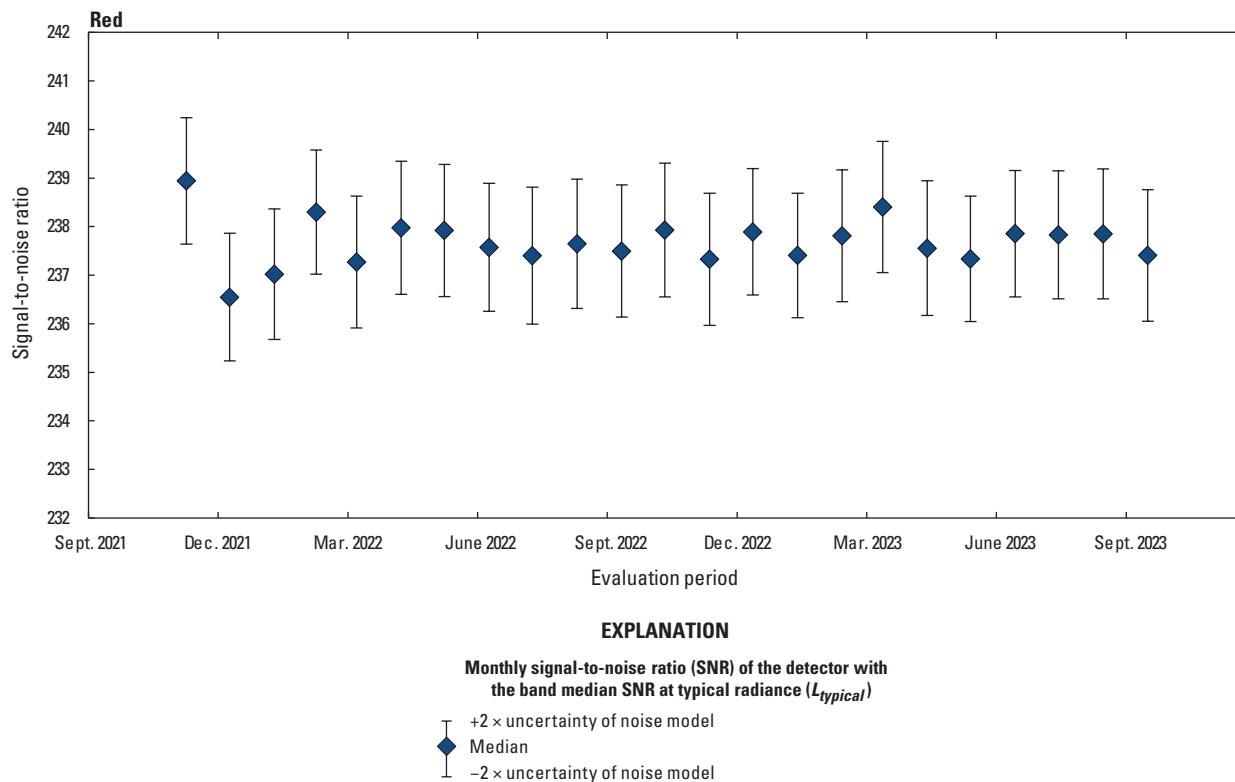


Figure 5. Landsat 9 Operational Land Imager red band lifetime signal-to-noise ratio stability.

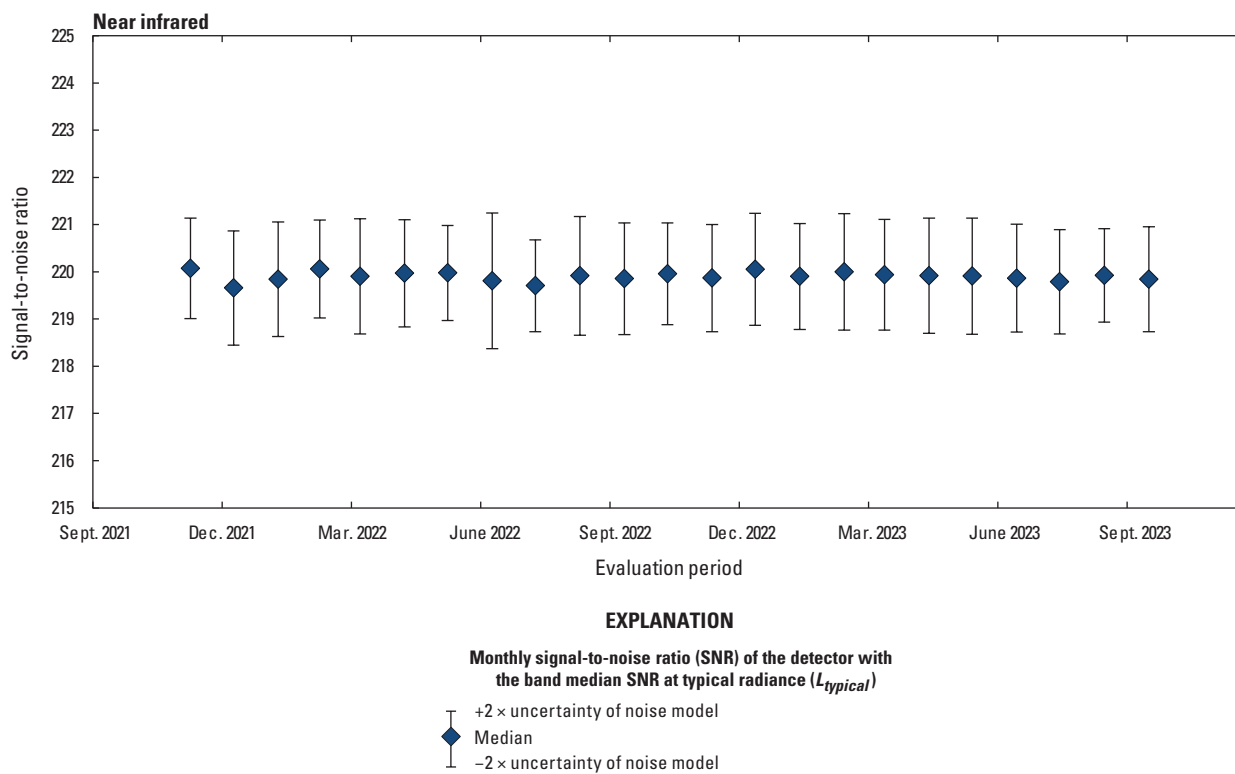


Figure 6. Landsat 9 Operational Land Imager near infrared band lifetime signal-to-noise ratio stability.

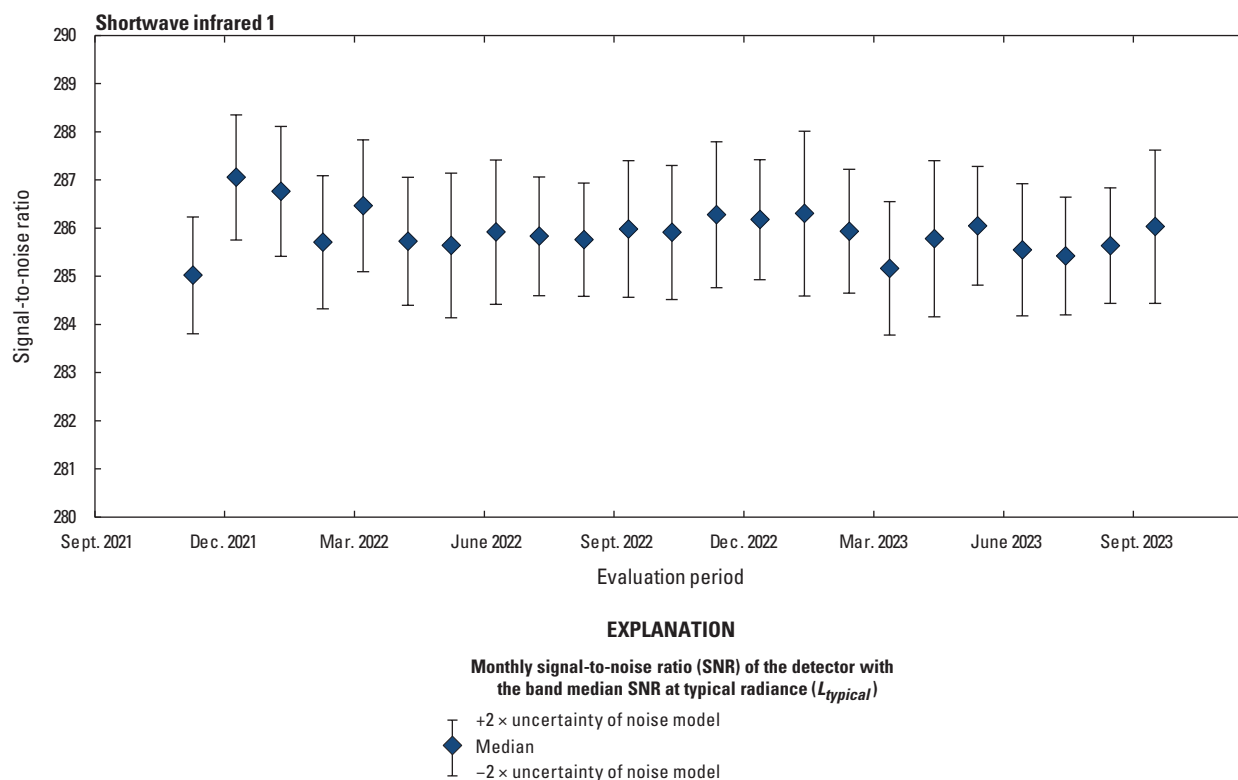


Figure 7. Landsat 9 Operational Land Imager shortwave infrared 1 band lifetime signal-to-noise ratio stability.

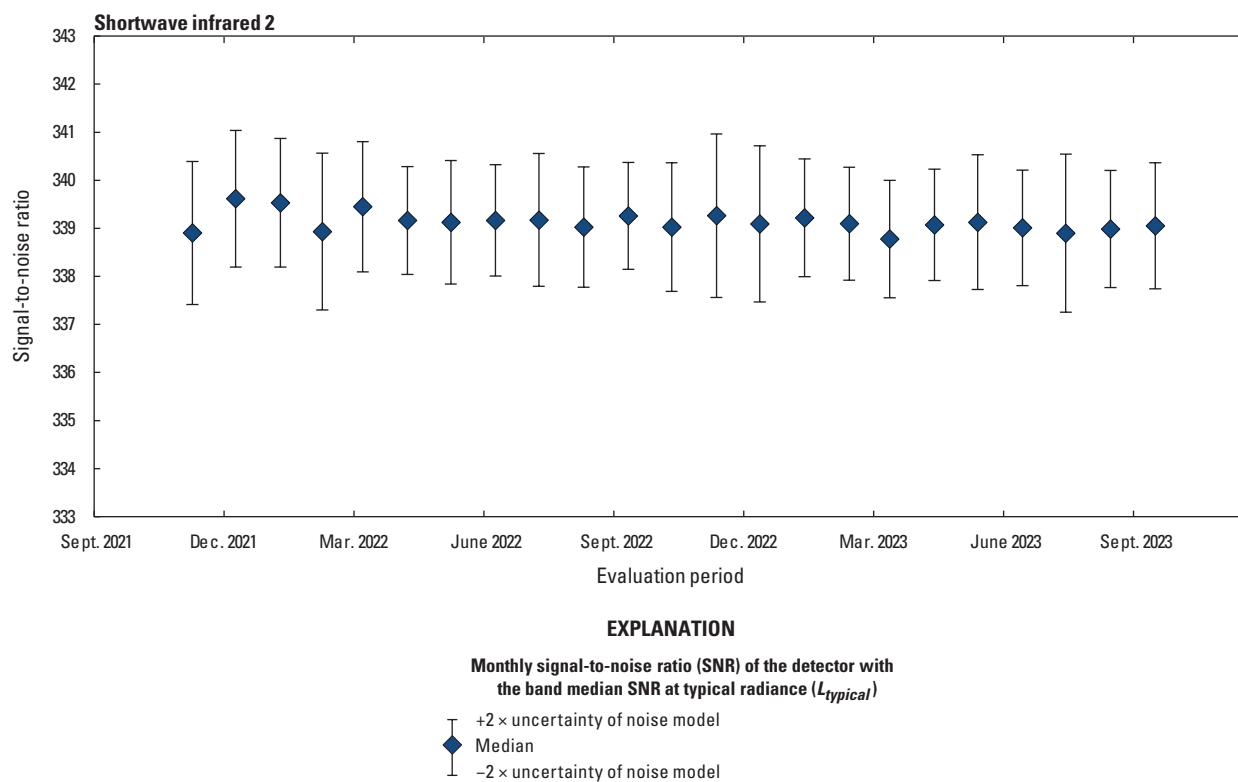


Figure 8. Landsat 9 Operational Land Imager shortwave infrared 2 band lifetime signal-to-noise ratio stability.

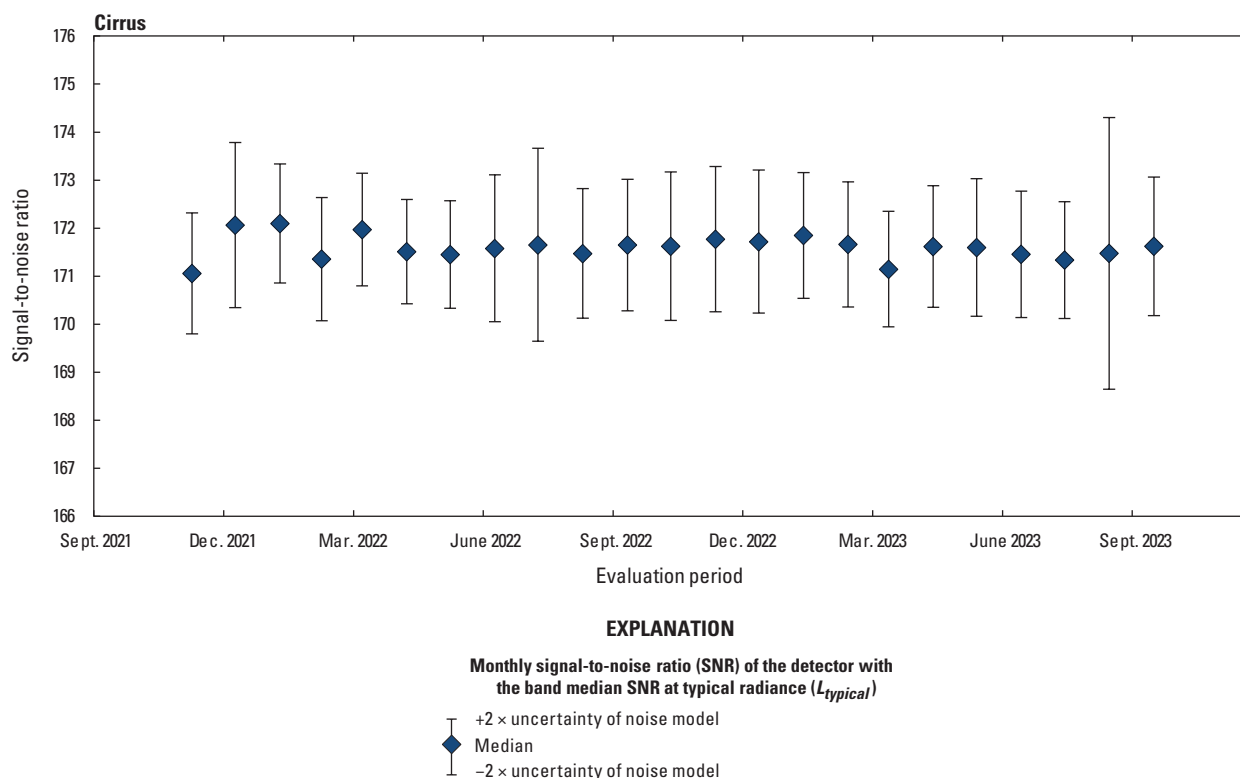


Figure 9. Landsat 9 Operational Land Imager cirrus band lifetime signal-to-noise ratio stability.

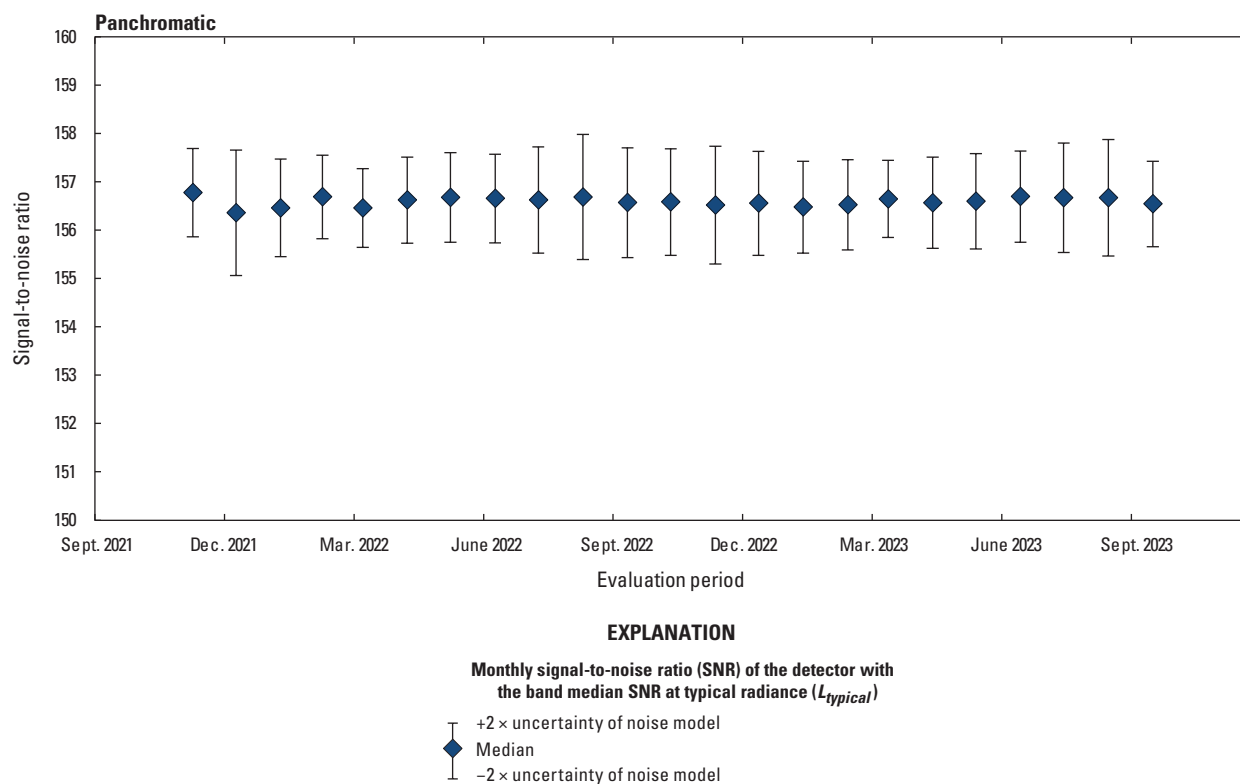


Figure 10. Landsat 9 Operational Land Imager panchromatic band lifetime signal-to-noise ratio stability.

in brightness temperature (that is, the noise equivalent change in temperature [NE Δ T]). NE Δ T is estimated as the standard deviation of detector data acquired over a uniform radiance source and then converted to temperature. Noise performance is completed on blackbody and deep space TIRS data (Barsi and others, 2022).

All Landsat 9 TIRS detectors have similar NE Δ T. At 300 Kelvin (K), band-average noise performance for both thermal bands is about six times better than the requirement (less than 0.4 K) and about three times better than the NE Δ T of the Landsat 7 ETM+ thermal band at that same temperature. Lifetime averages of NE Δ T at 300 K for TIRS band 10 are shown in figure 11, and the same averages for TIRS band 11 are shown in figure 12. In both figures, colored diamonds are used to indicate the observed NE Δ T values as measured over time.

Landsat 9 Radiometric Stability

Radiometric stability of an instrument is fundamental to low uncertainty in the radiometric calibration of data products generated from its measurements. The radiometric response stability is characterized for all OLI and TIRS bands using the instruments' responses to signals from the onboard calibration devices collected over time (USGS, 2021d). The bias and gain stability of an instrument are contributing factors to variability within a radiometrically calibrated product.

The per-band Landsat 9 OLI radiometric stability over the lifetime of the instrument is shown in figures 13, 14, 15, 16, 17, 18, 19, 20, and 21. Within each figure, the x-axis represents years since launch (September 27, 2021), and the y-axis

represents the response relative to the normalized first three months of image data acquisitions. All onboard calibrators demonstrate stable responses over time at a level less than approximately (~) 0.3 percent with no significant trends, indicating no change in responsivity of any band and indicating high radiometric stability of the instrument over its lifetime. Note that, because of the stable responses, the scale for these figures has been reduced when compared with the equivalent Landsat 8 figures to show additional detail.

Early mission TIRS responsivity remained stable to within 0.05 percent in bands 10 and 11. On March 12, 2022, the TIRS Cryocooler Electronics reset suddenly, leading to instrument power down and loss of thermal control. Once thermal control was recovered, the internal responsivity metric indicated that the response had changed by about 0.35 and 0.43 percent for bands 10 and 11. This is corrected during data product generation and is transparent to the data users. After the reset event, TIRS responsivity has remained stable, as shown in figures 22 and 23, respectively.

Landsat 9 Relative Gains

Relative gains account for the differences in responsivity between detectors within a spectral band. OLI relative gains are monitored using solar diffuser acquisitions, side slither acquisitions (which entail a 90-degree yaw maneuver over an invariant site to flatten the data), and scene statistics. Quarterly updates are completed using data from the solar diffuser acquisitions from the previous quarter (quarter 2 [April–June], 2023).

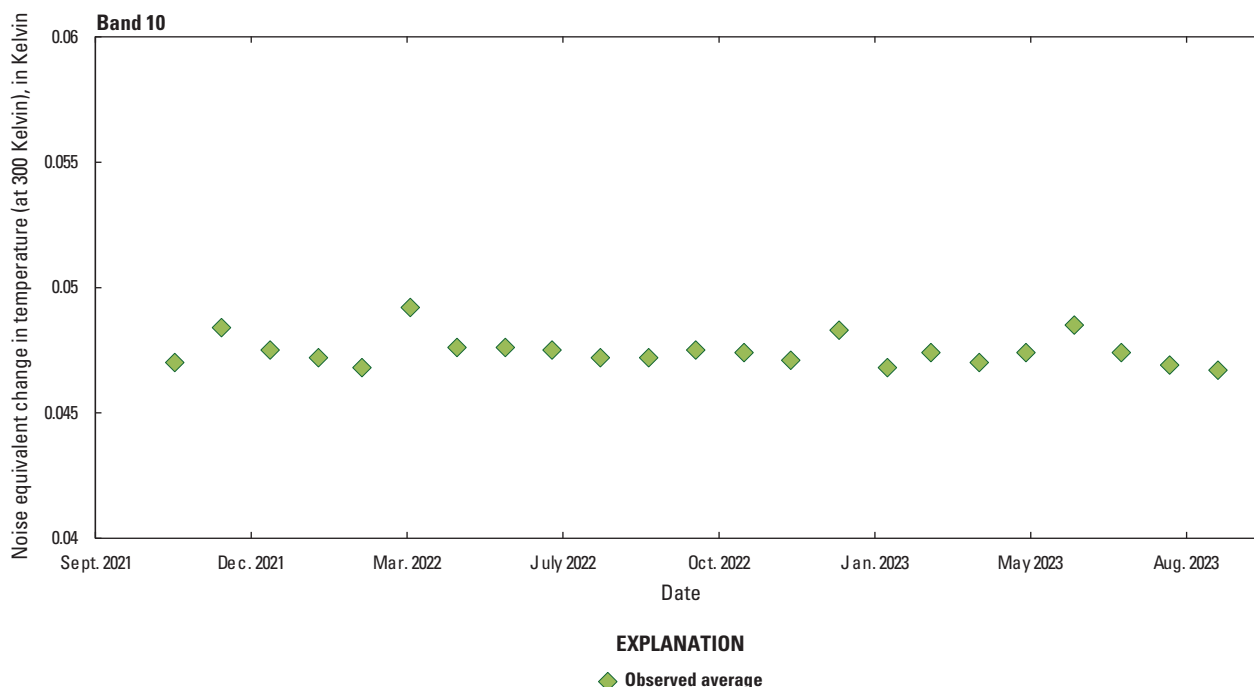


Figure 11. Landsat 9 Thermal Infrared Sensor band 10 lifetime noise performance.

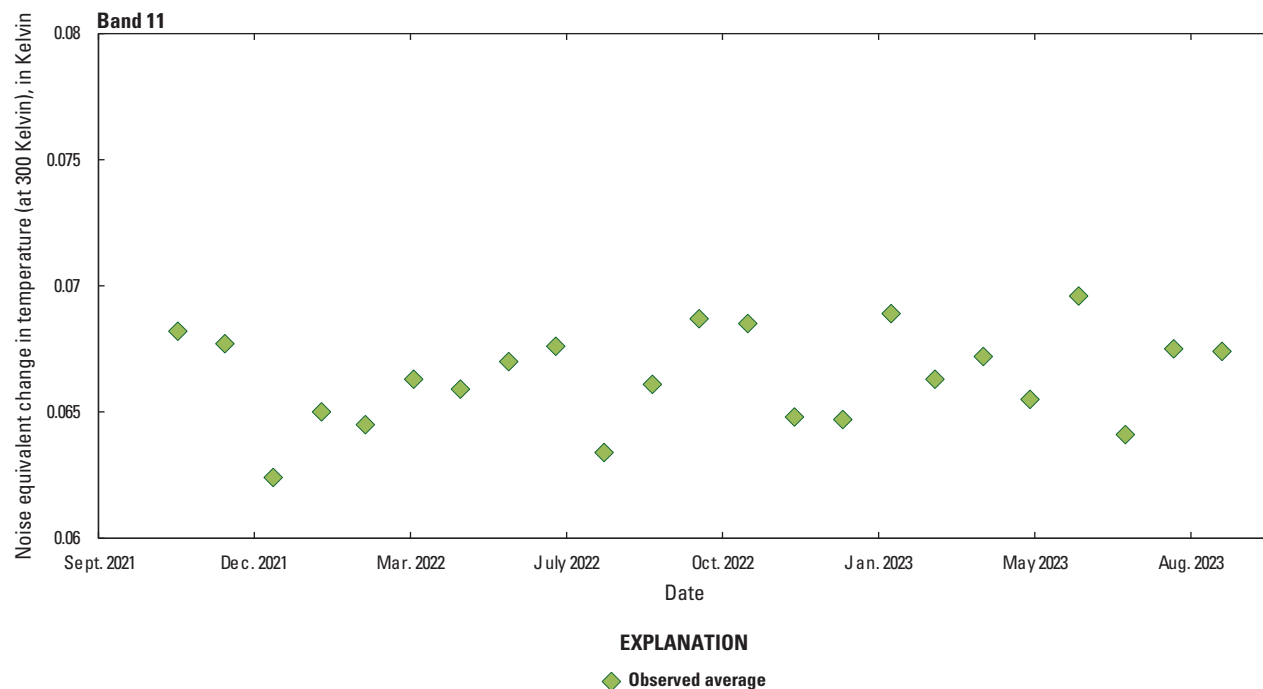


Figure 12. Landsat 9 Thermal Infrared Sensor band 11 lifetime noise performance.

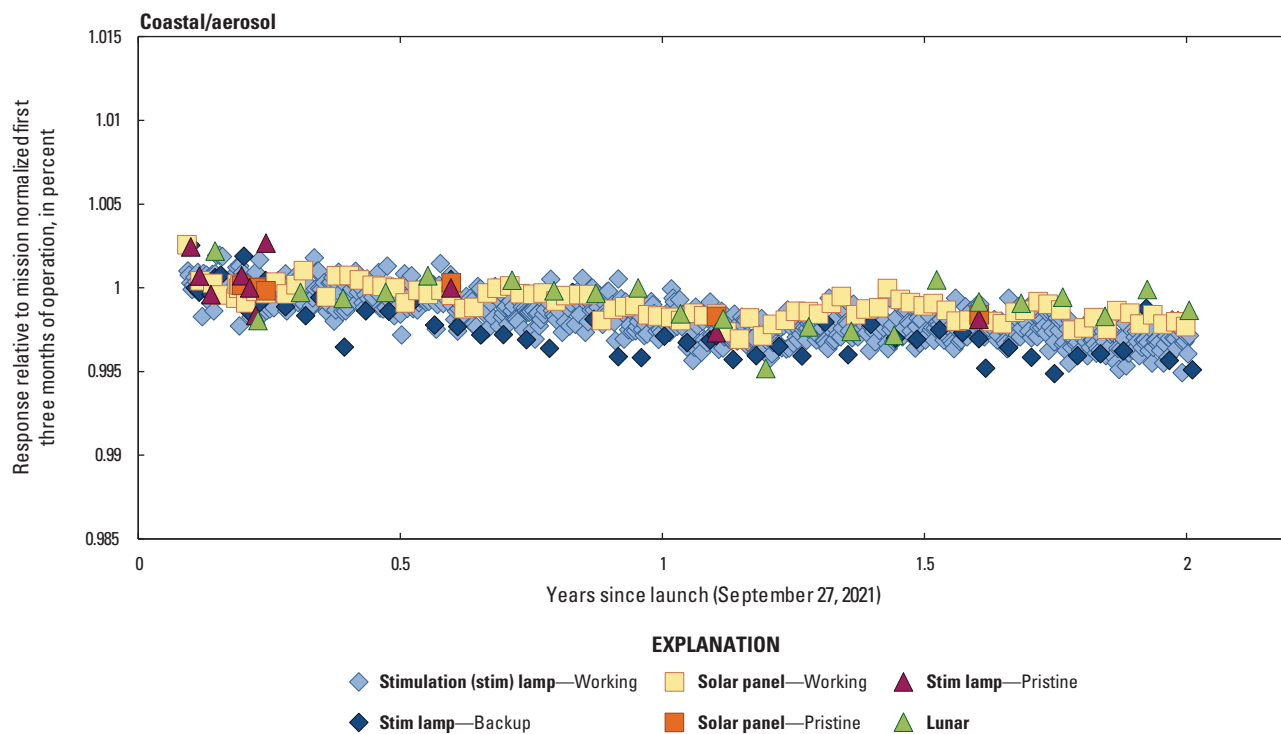


Figure 13. Landsat 9 Operational Land Imager coastal/aerosol band lifetime radiometric stability.

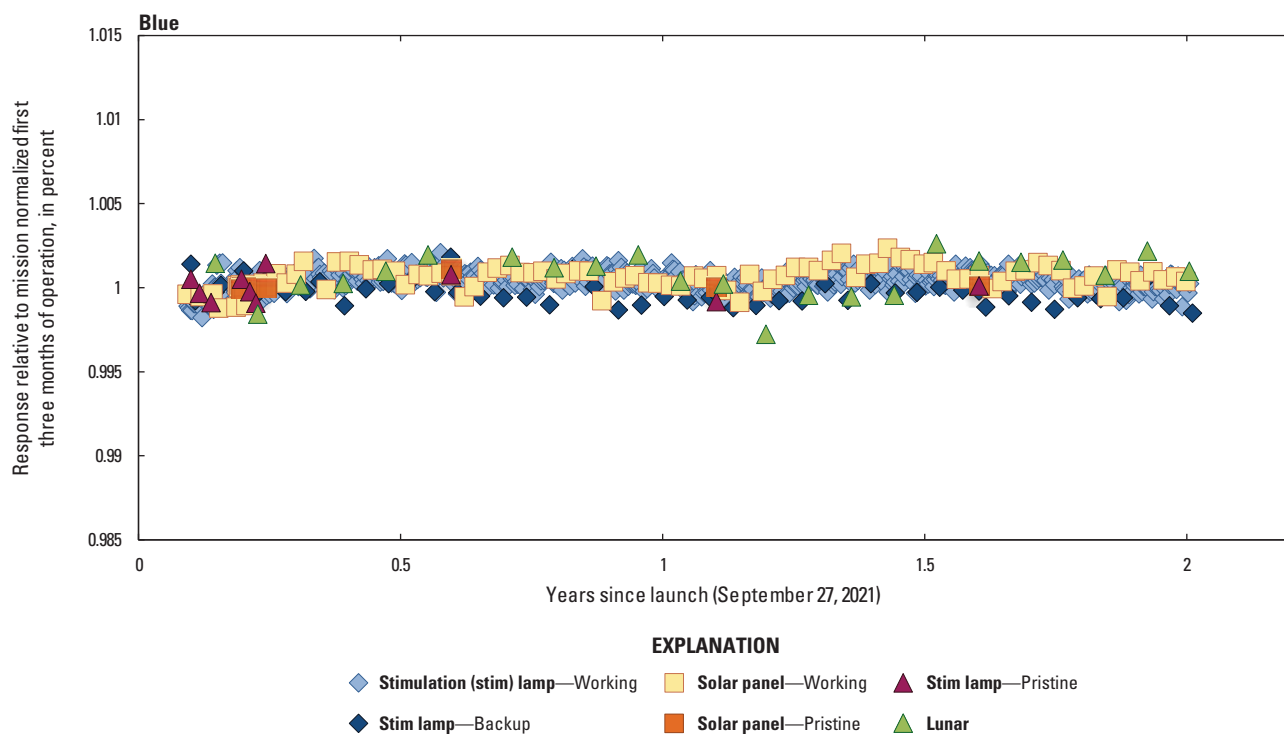


Figure 14. Landsat 9 Operational Land Imager blue band lifetime radiometric stability.

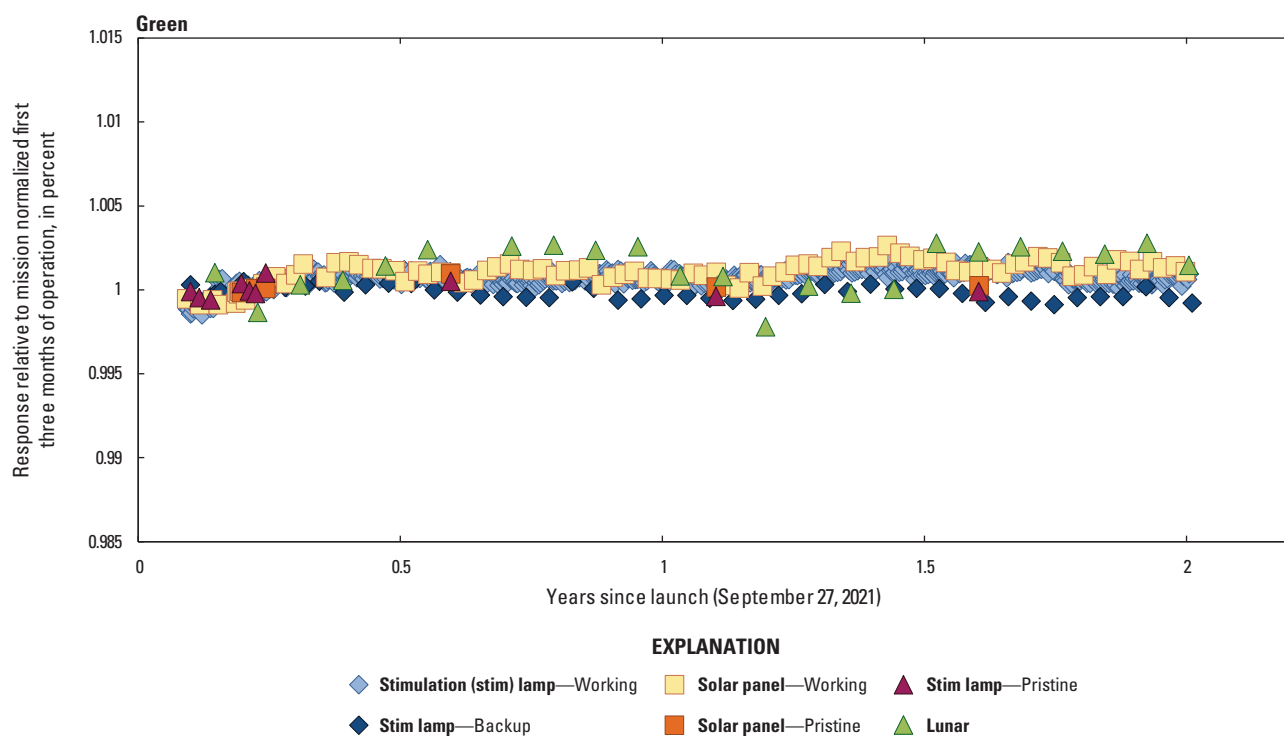


Figure 15. Landsat 9 Operational Land Imager green band lifetime radiometric stability.

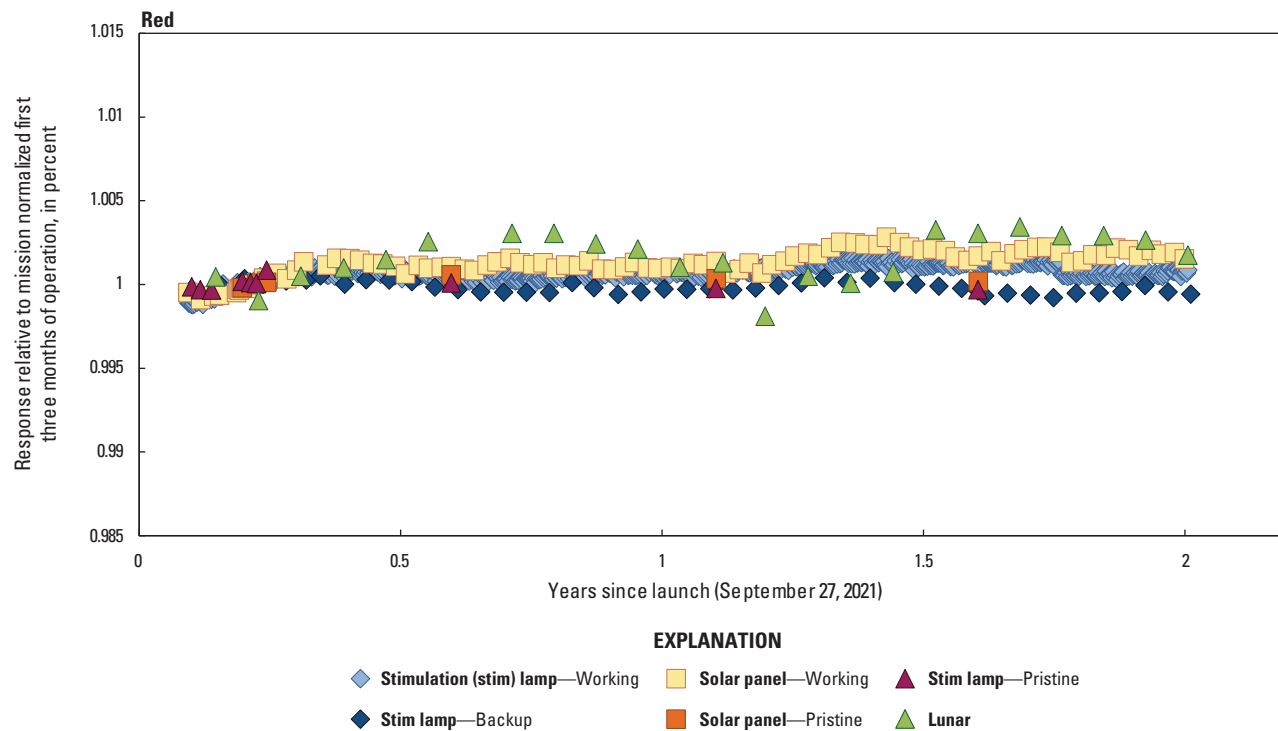


Figure 16. Landsat 9 Operational Land Imager red band lifetime radiometric stability.

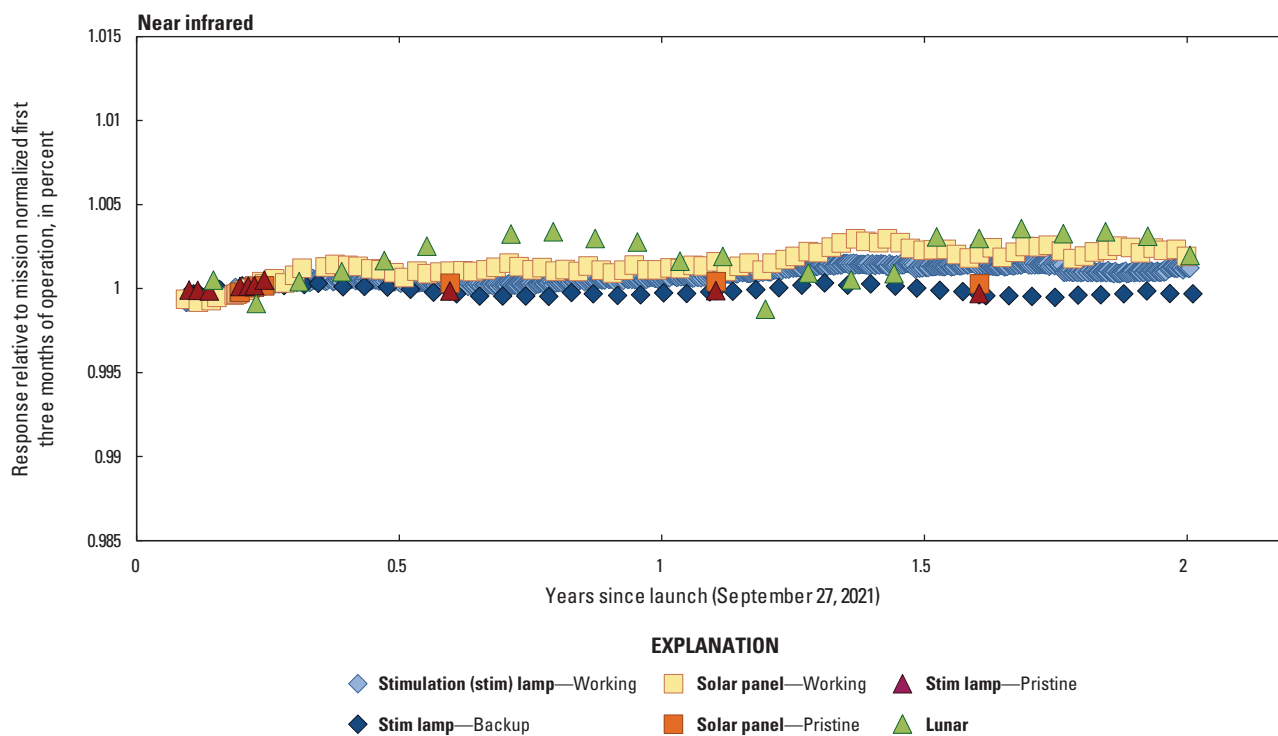


Figure 17. Landsat 9 Operational Land Imager near infrared band lifetime radiometric stability.

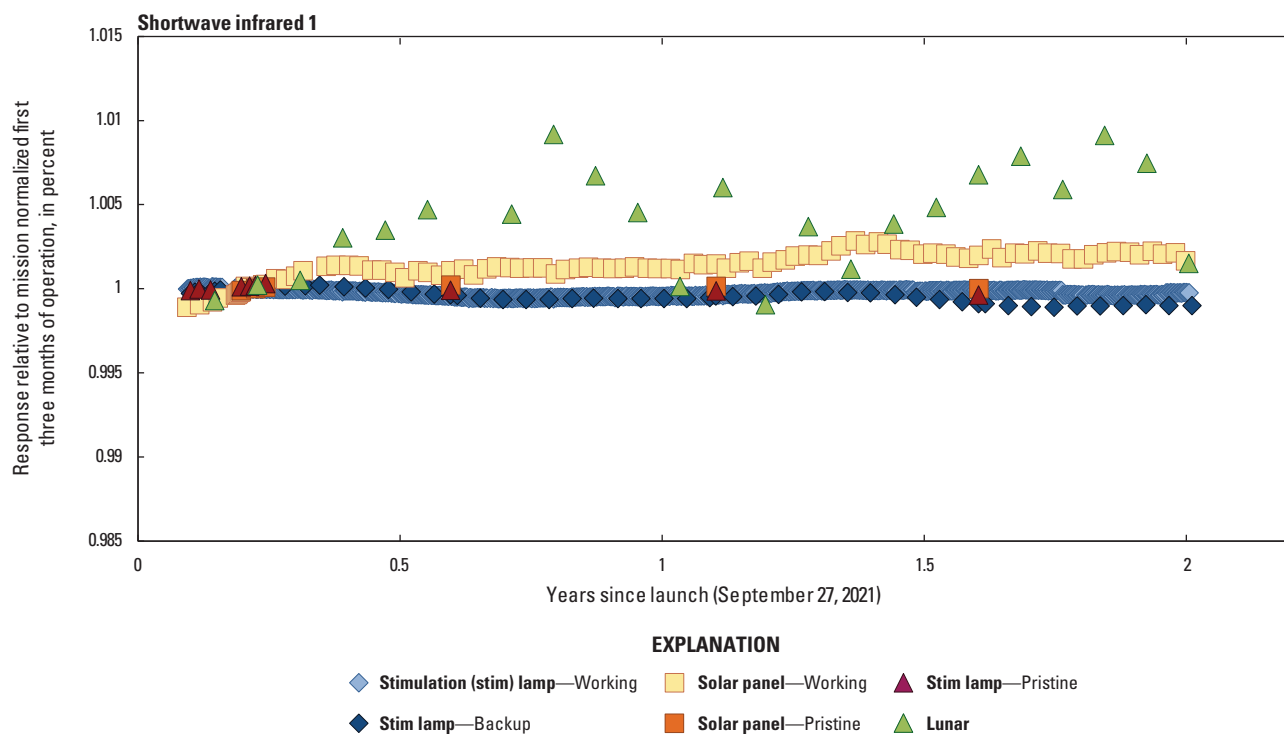


Figure 18. Landsat 9 Operational Land Imager shortwave infrared 1 band lifetime radiometric stability.

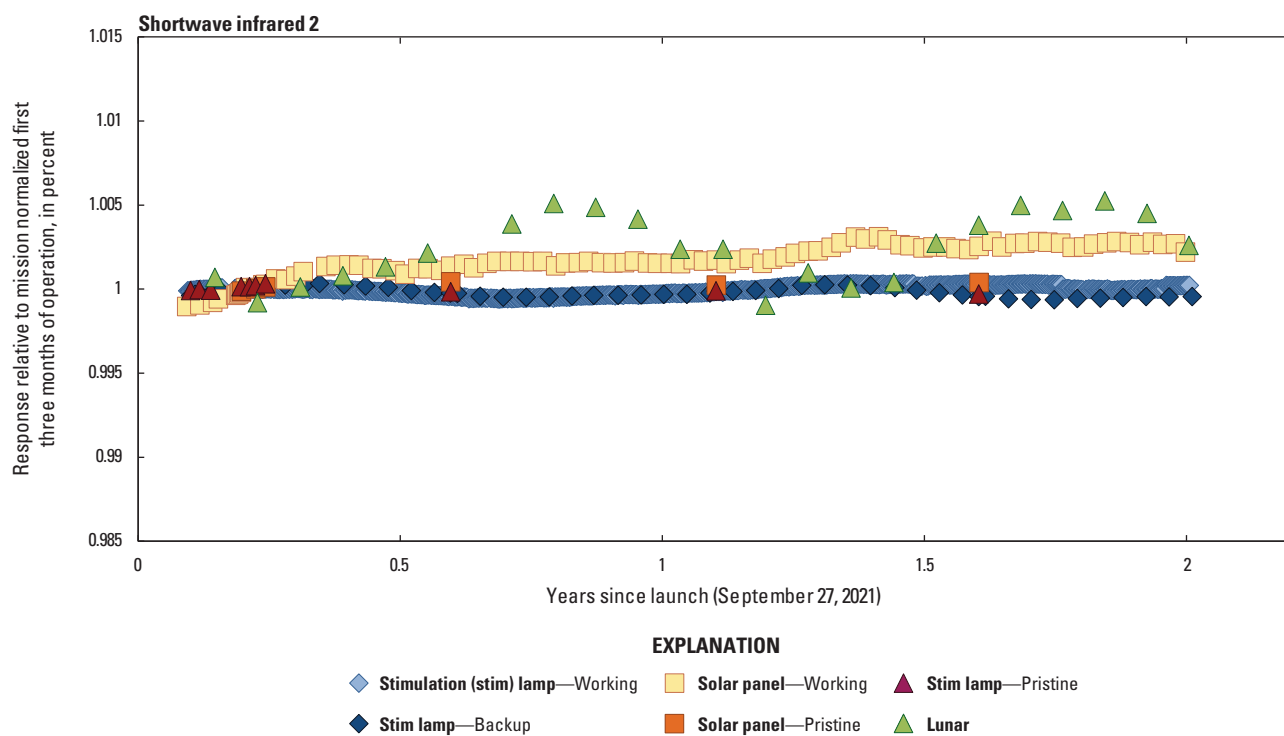


Figure 19. Landsat 9 Operational Land Imager shortwave infrared 2 band lifetime radiometric stability.

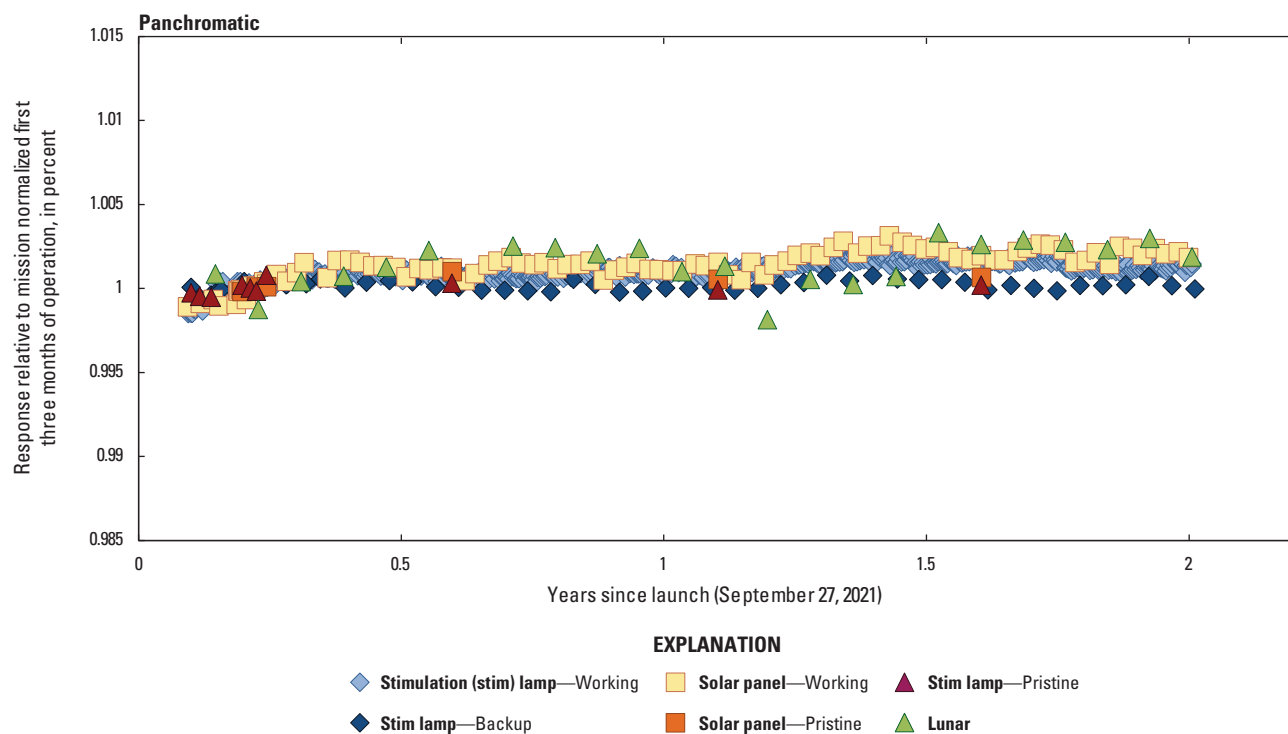


Figure 20. Landsat 9 Operational Land Imager panchromatic band lifetime radiometric stability.

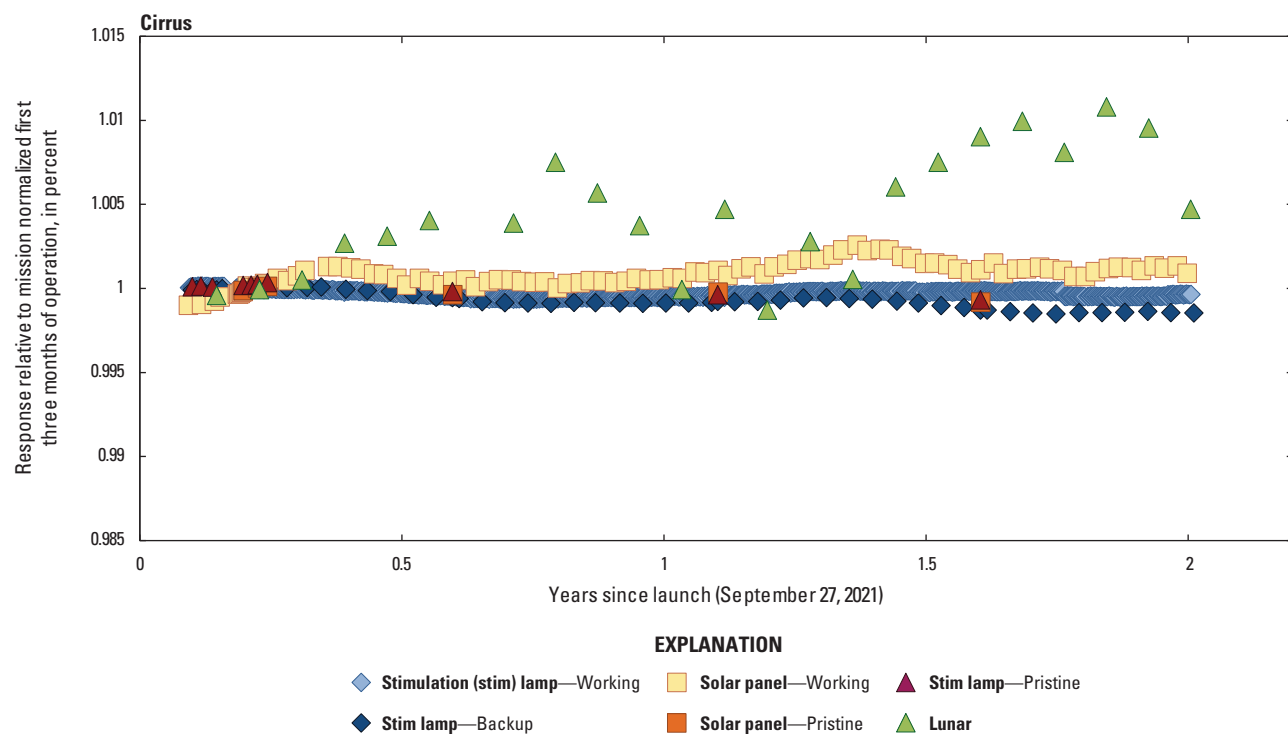


Figure 21. Landsat 9 Operational Land Imager cirrus band lifetime radiometric stability.

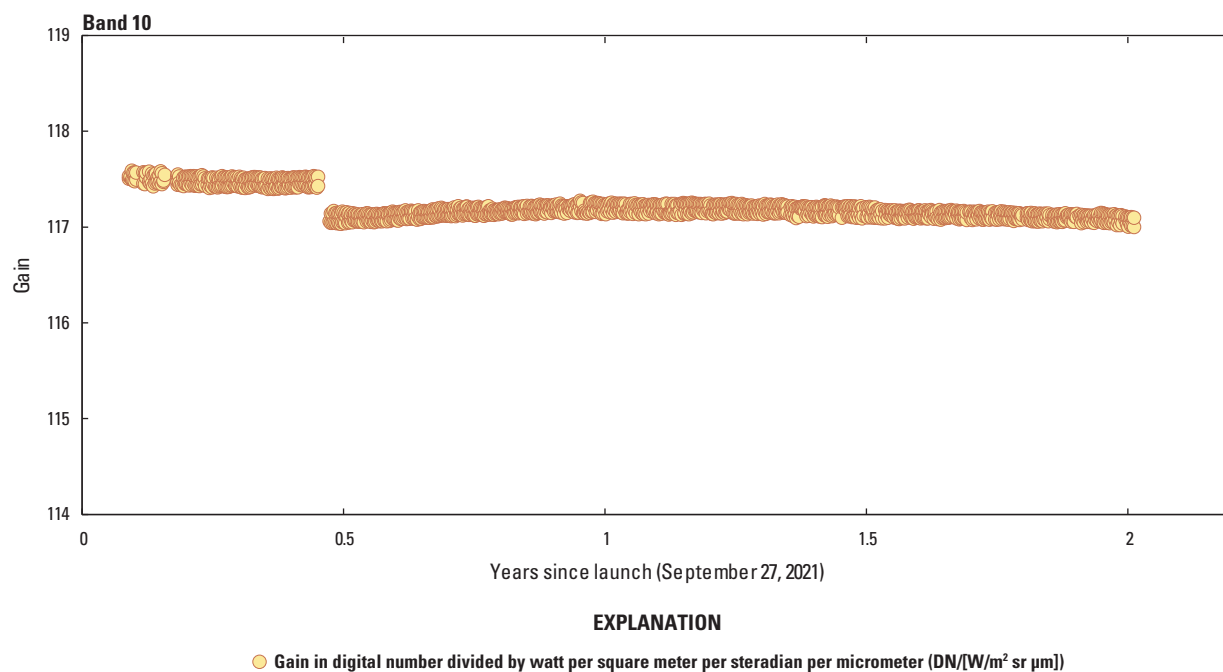


Figure 22. Landsat 9 Thermal Infrared Sensor band 10 radiometric stability.

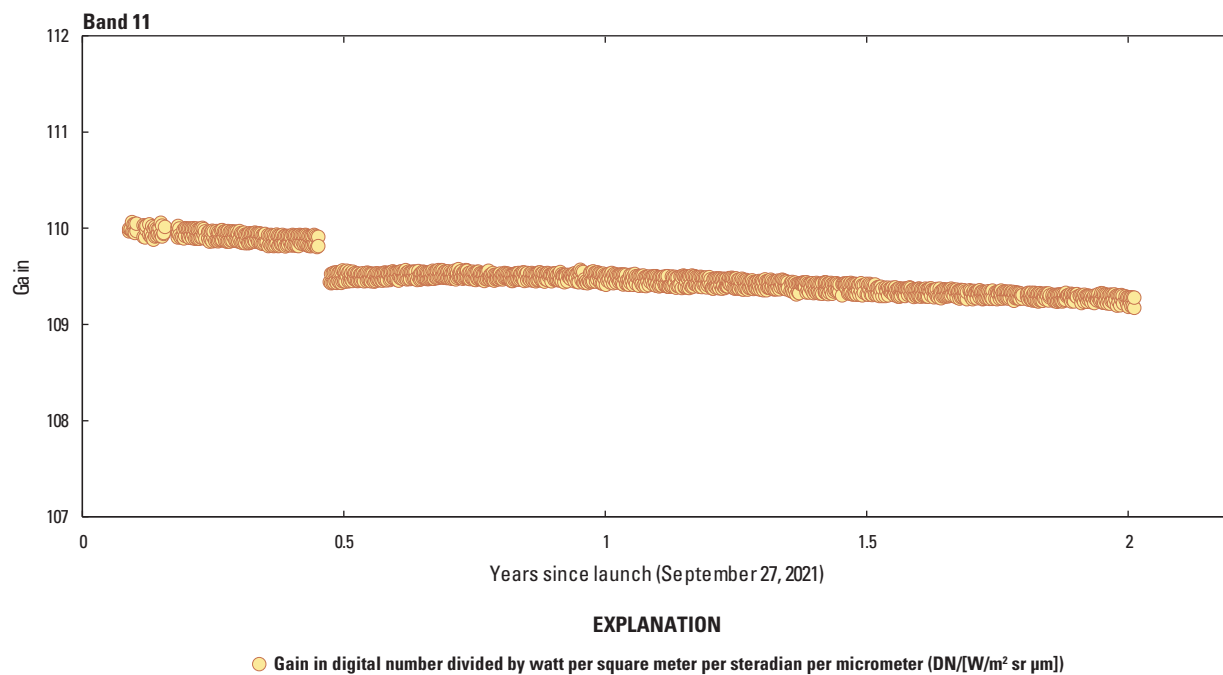


Figure 23. Landsat 9 Thermal Infrared Sensor band 11 radiometric stability.

Typical per-detector changes in relative gains between the previous quarter and this quarter for several bands are shown in [figures 24, 25, 26, and 27](#) by analyzing data from within each quarter. In each figure, the x-axis indicates the detector index, and the y-axis indicates the change in relative gain between the quarters as a ratio. These changes in responsivity are accounted for in the L1 product by updating the following quarter's calibration parameter file (CPF).

The Landsat 9 OLI detectors that have indicated a sudden change in responsivity of 0.5 percent or greater in the short-wave infrared (SWIR) 1 and SWIR 2 bands since launch are shown in [figures 28 and 29](#). The x-axis indicates the date of the jump in responsivity, and the y-axis signifies the detector number. The observed responsivity jumps seem to be randomly scattered in time and location on the focal plane so do not seem to be associated with an instrument event or failure. These jumps are only observed in the SWIR bands (SWIR 1, SWIR 2, and cirrus); the visible and near infrared band detectors have not indicated any jump behavior over the whole mission.

Landsat 9 to Landsat 8 Operational Land Imager Radiometric Cross-Correlation

The instruments onboard Landsat 9 are improved replicas of those currently collecting data onboard Landsat 8. Landsat 9 improvements include higher OLI radiometric resolution with a 14-bit quantization, increased from 12 bits for Landsat 8 (USGS, 2019c). Cross-correlation quantitative analysis between the Landsat 9 and Landsat 8 Level 1 top of atmosphere reflectance acquisitions over a pseudoinvariant calibration site (PICS) is performed to determine interoperability between Landsat 9 OLI and Landsat 8 OLI.

The top of atmosphere reflectance values observed over the Libya 4 PICS site (lat 28.55° N., long 23.39° E.) using the Centre National D'Etudes Spatiales (CNES) region of interest (ROI) are shown in [figure 30](#). The reflectance measurements indicate good agreement between both sensors, and the similar trends by both sensors indicate consistent calibration.

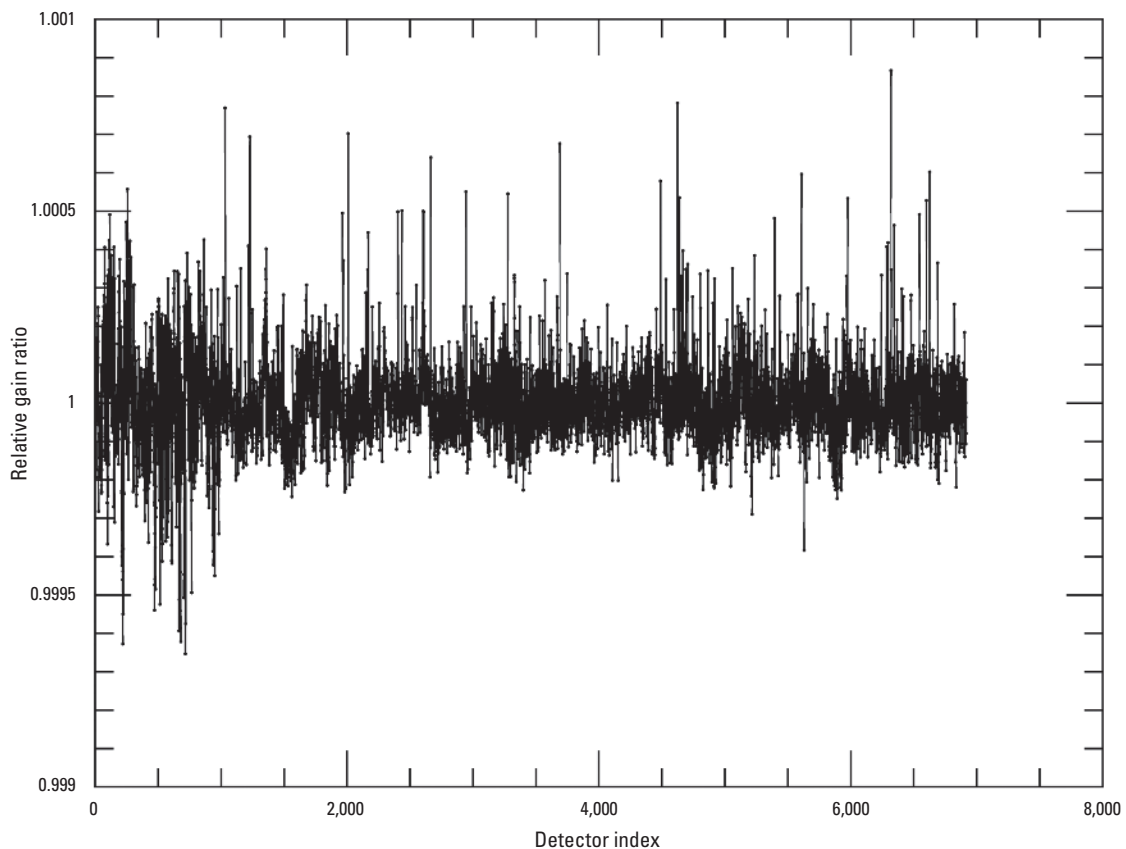


Figure 24. Landsat 9 Operational Land Imager coastal/aerosol band per-detector change in relative gains between quarter 2 and quarter 3, 2023.

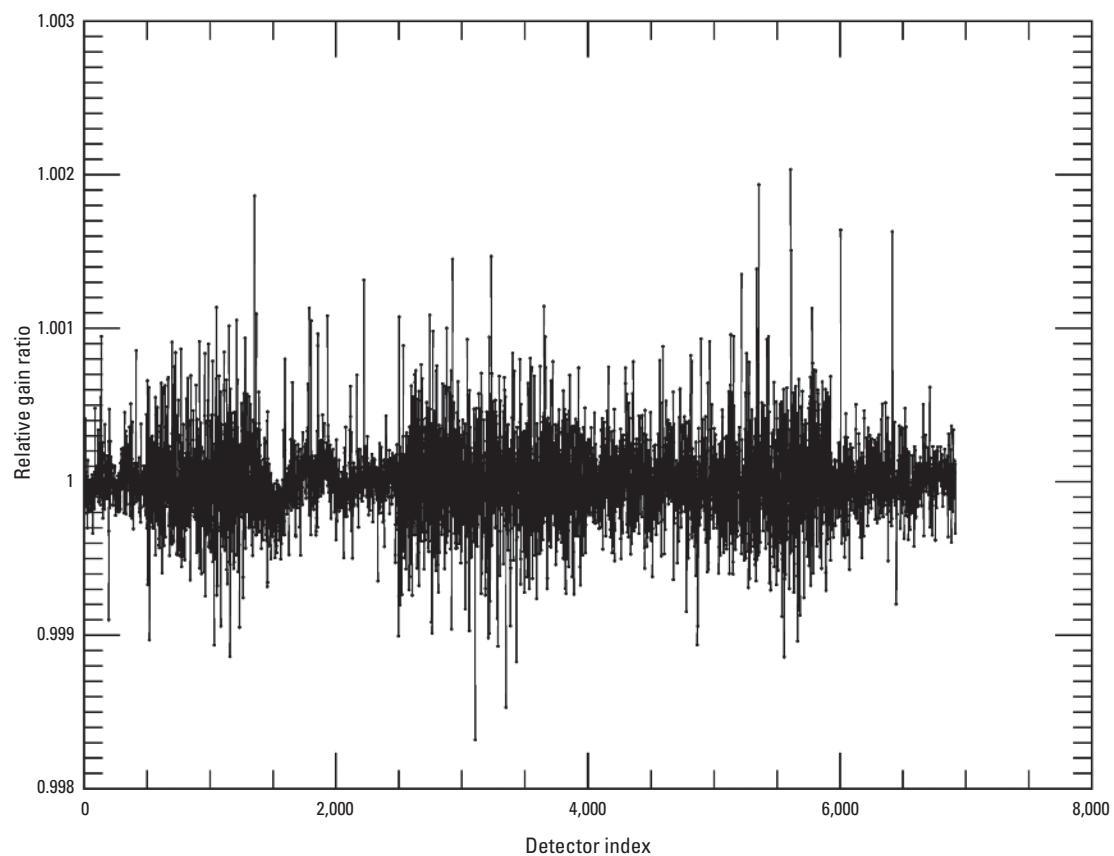


Figure 25. Landsat 9 Operational Land Imager shortwave infrared 1 band per-detector change in relative gains between quarter 2 and quarter 3, 2023.

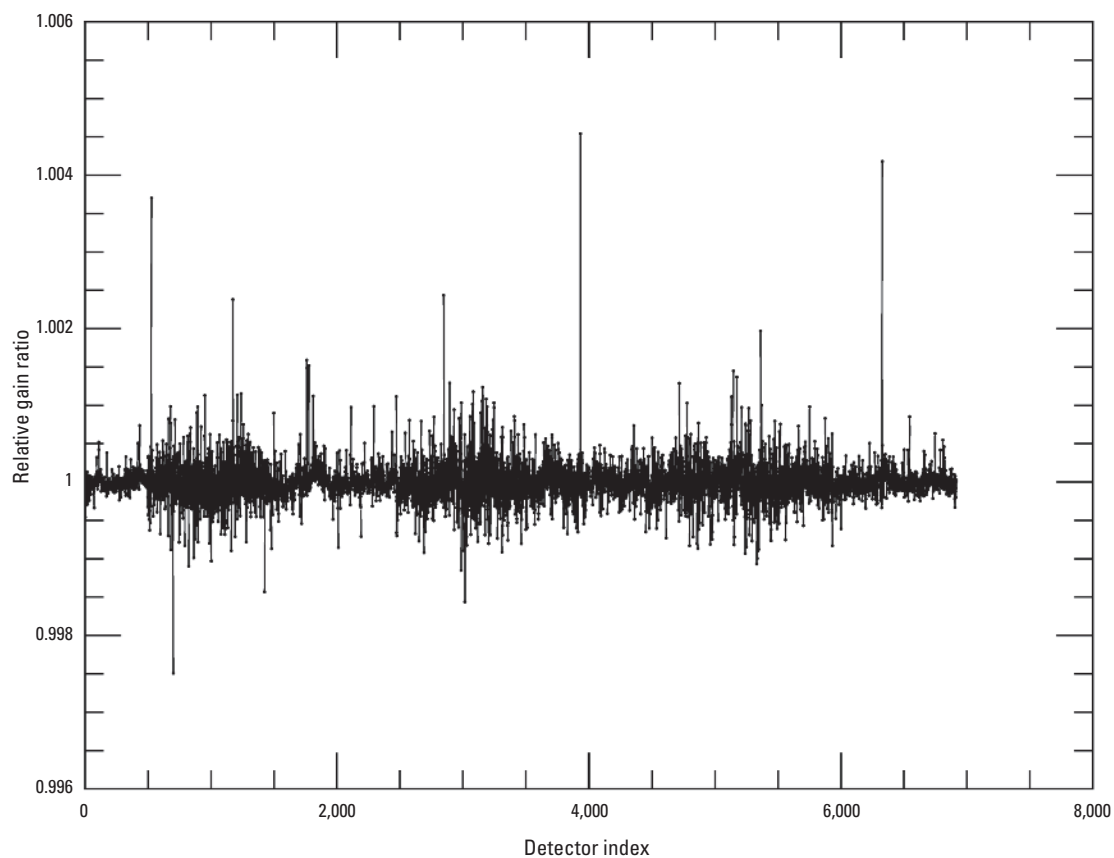


Figure 26. Landsat 9 Operational Land Imager shortwave infrared 2 band per-detector change in relative gains between quarter 2 and quarter 3, 2023.

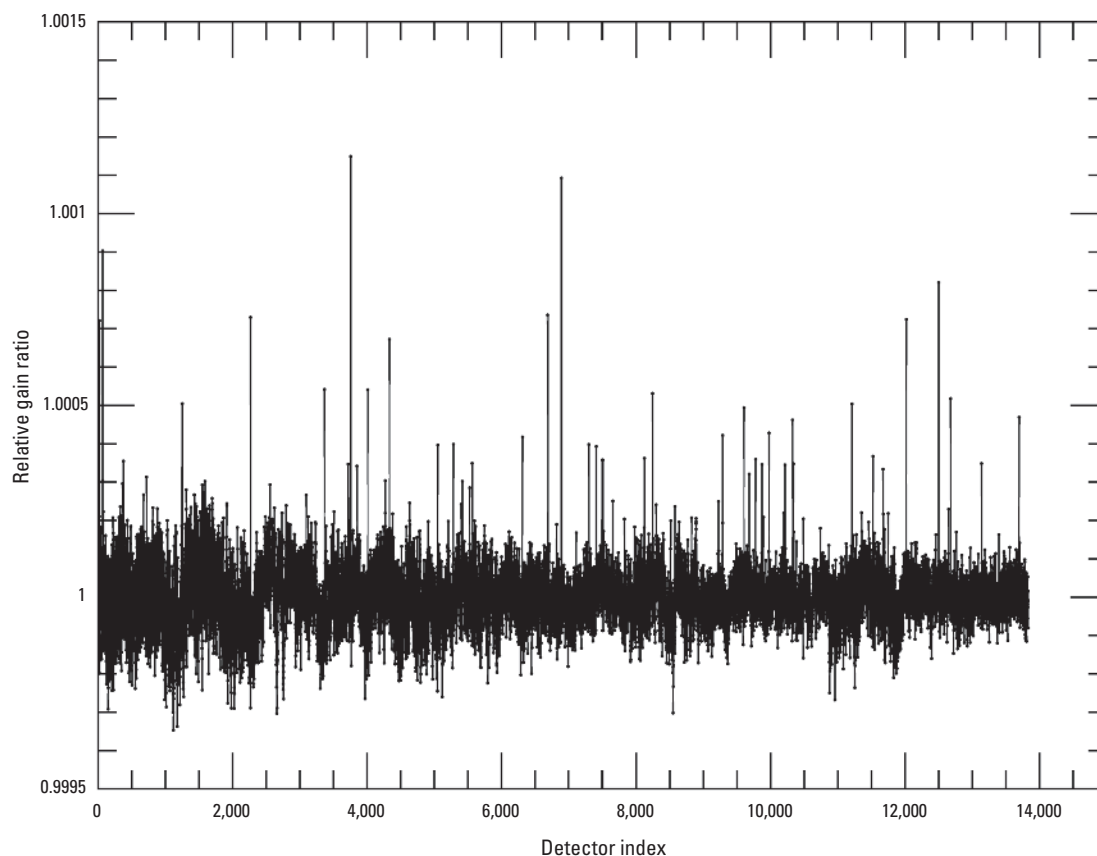


Figure 27. Landsat 9 Operational Land Imager panchromatic band per-detector change in relative gains between quarter 2 and quarter 3, 2023.

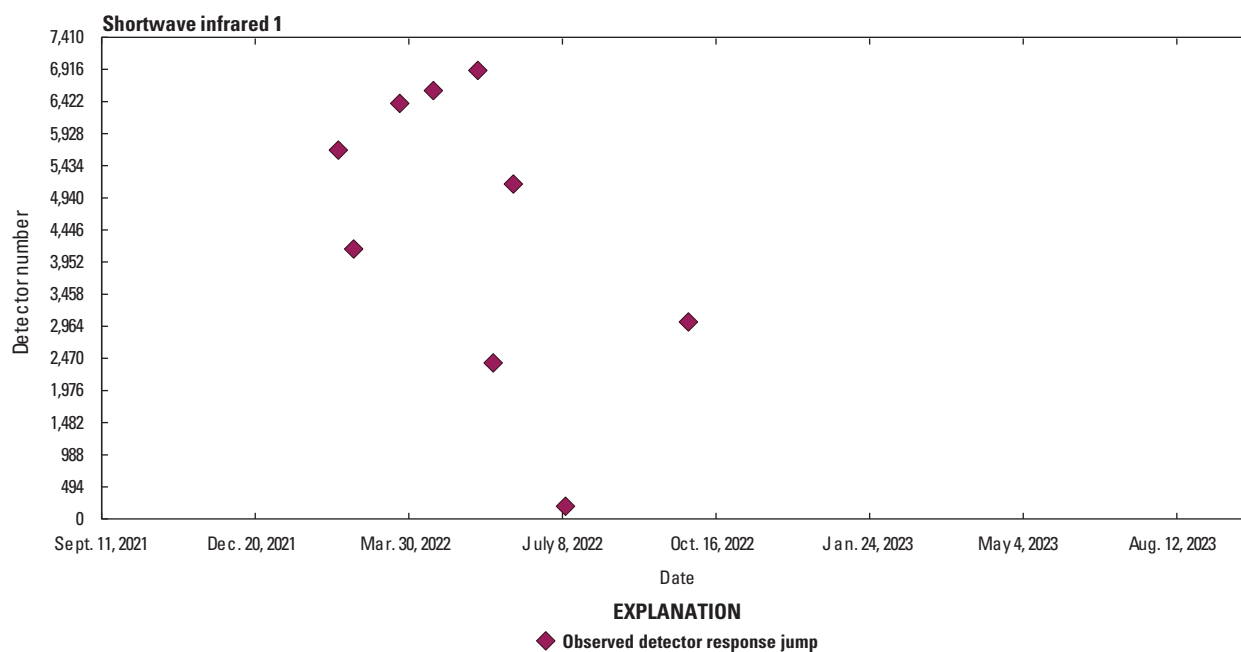


Figure 28. Landsat 9 Operational Land Imager shortwave infrared 1 lifetime jumps in detector responsivity.

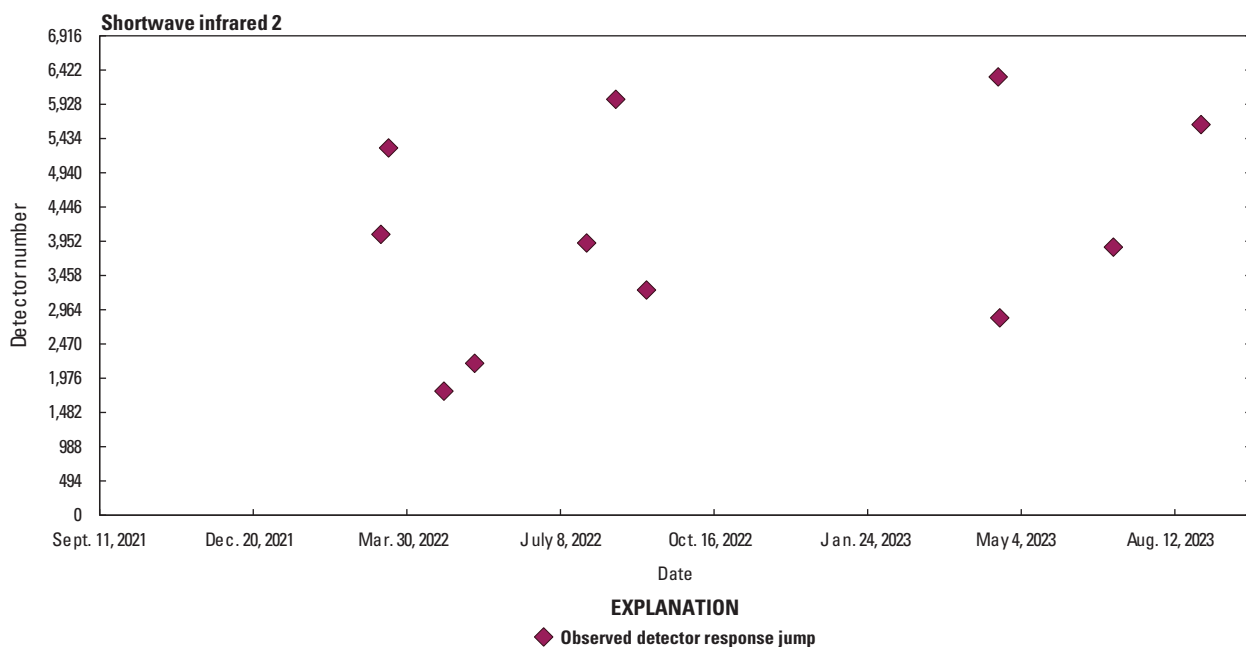


Figure 29. Landsat 9 Operational Land Imager shortwave infrared 2 lifetime jumps in detector responsivity.

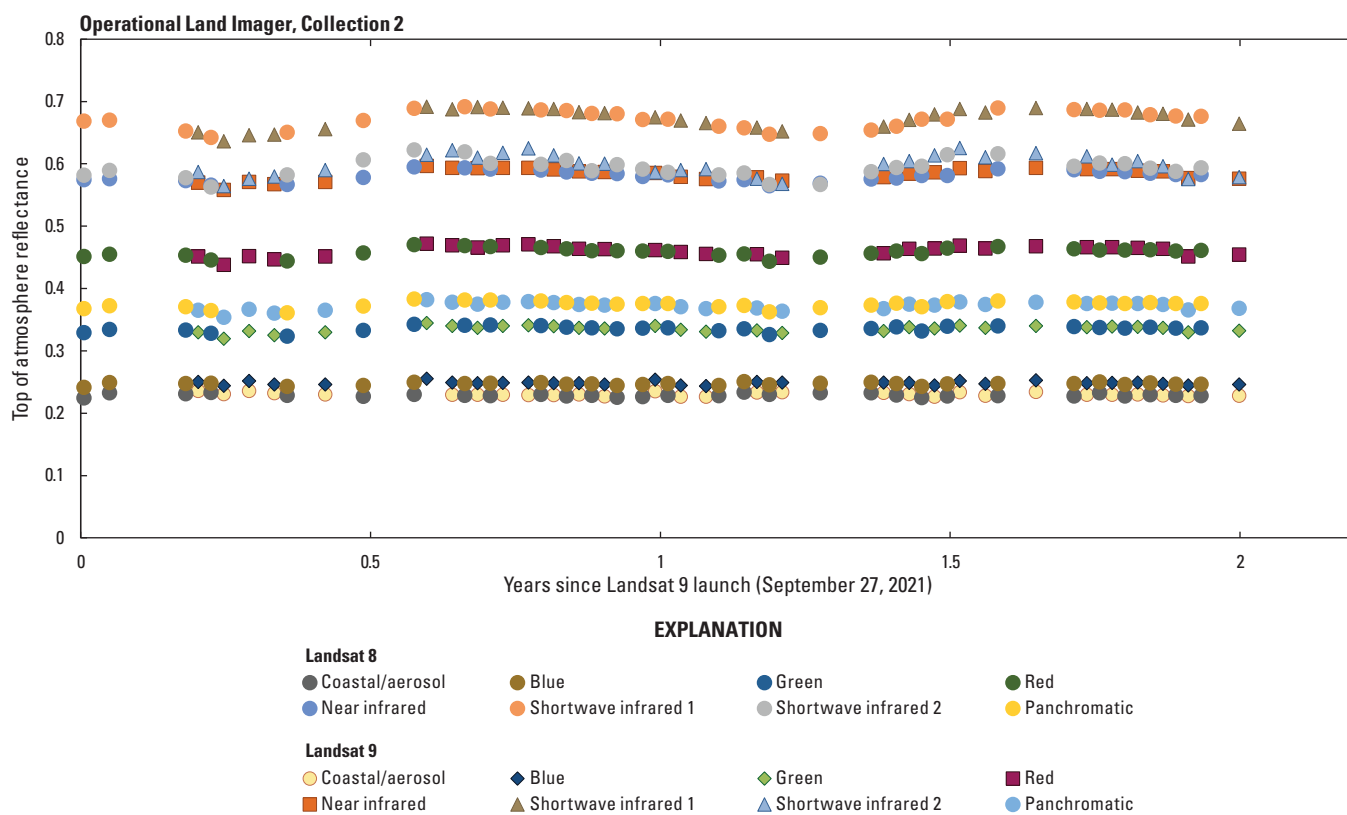


Figure 30. Landsat 9 to Landsat 8 Operational Land Imager Libya 4 pseudoinvariant calibration site top of atmosphere reflectance cross-correlation.

Landsat 9 Geometric Performance Summary

The Landsat 9 on-orbit geometric performance for the reporting quarter (quarter 3, July–September 2023) meets all requirements as outlined in USGS (2022). The quarterly results summary is provided in [table 4](#).

Landsat 9 Band Registration Accuracy

Internal band registration measures how accurately the various Landsat 9 spectral bands are geometrically aligned to each other. The assessment provides a numerical evaluation of the accuracy of the band registration within an image using automated cross-correlation techniques between the bands to be assessed (USGS, 2021d).

Landsat 9 OLI band registration performance has been stable over time. Quarterly band-to-band maximum registration accuracy for each band combination except for the cirrus band is shown in [figure 31](#). Within the figure, blue bars indicate maximum registration accuracy in the line direction, and green bars indicate maximum registration accuracy in the sample direction. Lifetime OLI band registration accuracy for all bands is 4.5 meters (not shown), and lifetime OLI band registration accuracy for all bands, excluding cirrus, is 3.2 meters, which is well within the instrument specification accuracy. OLI band registration accuracy for all bands during quarter 3, 2023, is 4.5 meters (not shown), and OLI band registration accuracy for all bands, excluding cirrus, during quarter 3, 2023, is 3.3 meters.

TIRS band registration performance has been stable throughout the instrument’s lifetime. Behavior is well within specification, as shown in [figure 32](#), and quarter 3, 2023, results are consistent with past performance. Within the figure, blue bars indicate maximum registration accuracy in the

line direction, and green bars indicate maximum registration accuracy in the sample direction. Lifetime TIRS band registration accuracy is 8.4 meters, and during quarter 3, 2023, the accuracy is 8.8 meters.

Lifetime TIRS to OLI band registration accuracy by quarter is shown in [figure 33](#). Behavior has been stable throughout the instrument’s lifetime and well within specification. Within the figure, blue bars indicate maximum registration accuracy in the line direction, and green bars indicate maximum registration accuracy in the sample direction. Lifetime TIRS to OLI registration accuracy (excluding the cirrus band) is 17.8 meters in the line direction and 17.7 meters in the sample direction. Quarter 3, 2023, TIRS to OLI registration accuracy (excluding the cirrus band) is 17.4 meters in the line direction and 17.1 meters in the sample direction.

Landsat 9 Operational Land Imager to Thermal Infrared Sensor Alignment

Landsat 9 OLI to TIRS alignment knowledge is critical to ensure that the L1 product accuracy requirements can be met. The alignment between OLI and TIRS instruments is periodically measured using correlation-based methods to ensure that the band-to-band alignment requirements for all Landsat 9 bands can be met (USGS, 2021d). The alignment estimates are used to update the calibration parameters in the CPFs when the observed changes are determined to affect the performance requirements.

TIRS to OLI pitch alignment measurements over instrument lifetimes are shown in [figure 34](#). Although still early in the Landsat 9 mission, a seasonal pattern has been observed along with a slight downward trend. The predictive estimate for quarter 4, 2023, was determined based on these observed trends. The lifetime TIRS to OLI roll alignment is shown in [figure 35](#), and the lifetime TIRS to OLI yaw alignment is shown in [figure 36](#). Each light blue symbol on these figures

Table 4. Landsat 9 geometric performance summary, quarter 3 (July–September), 2023.

[The previous quarter is quarter 2 (April–June), 2023. OLI, Operational Land Imager; <, less than; LE90, linear error with 90-percent confidence; CE90, circular error with 90-percent confidence; L1T, Level 1 terrain-corrected product; >, greater than; TIRS, Thermal Infrared Sensor]

Requirement	Measured value from this quarter	Measured value from previous quarter	Required value	Unit
OLI band registration accuracy (all bands)	4.48	4.45	<4.5	Meter (LE90)
OLI band registration accuracy (no cirrus)	3.30	3.24	<4.5	Meter (LE90)
Absolute geodetic accuracy	11.4	26.2	<65	Meter (CE90)
Relative geodetic accuracy	7.5	7.5	<25	Meter (CE90)
Geometric (L1T) accuracy	8.4	11.4	<12	Meter (CE90)
OLI edge slope	0.029	0.030	>0.027	1 per meter
TIRS band registration accuracy	8.8	8.6	<18	Meter (LE90)
TIRS-to-OLI registration accuracy	17.4	17.2	<30	Meter (LE90)

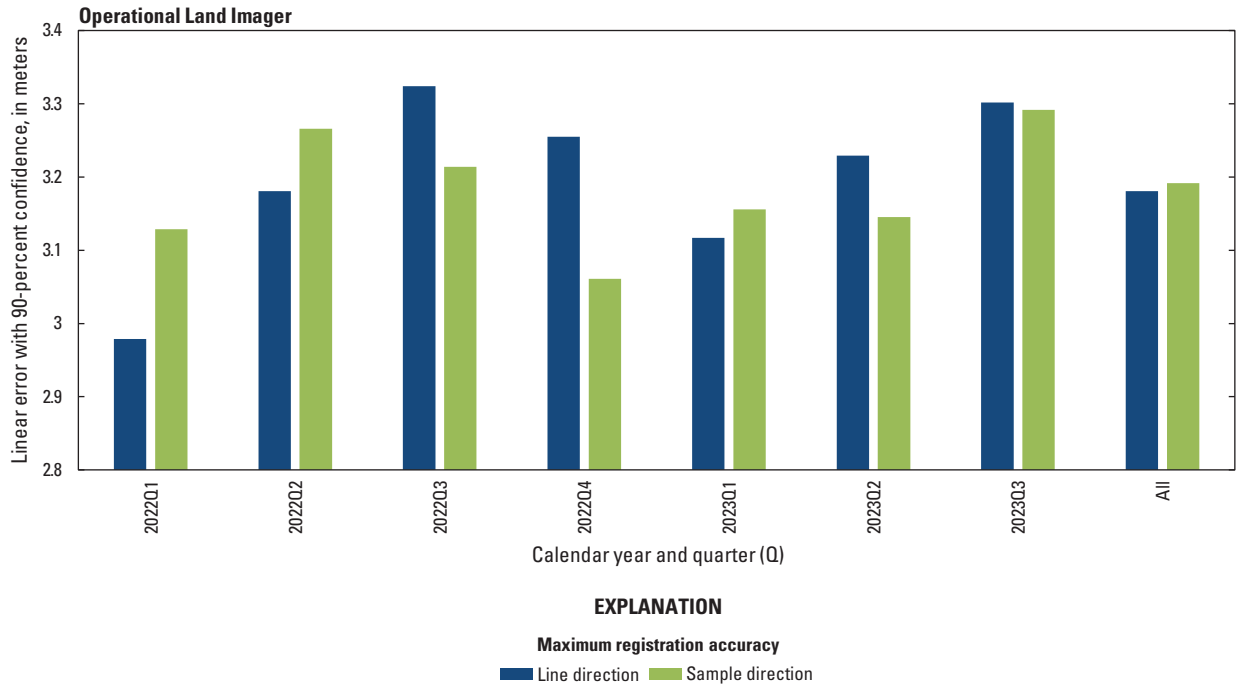


Figure 31. Landsat 9 Operational Land Imager lifetime band (excluding cirrus) registration accuracy by quarter.

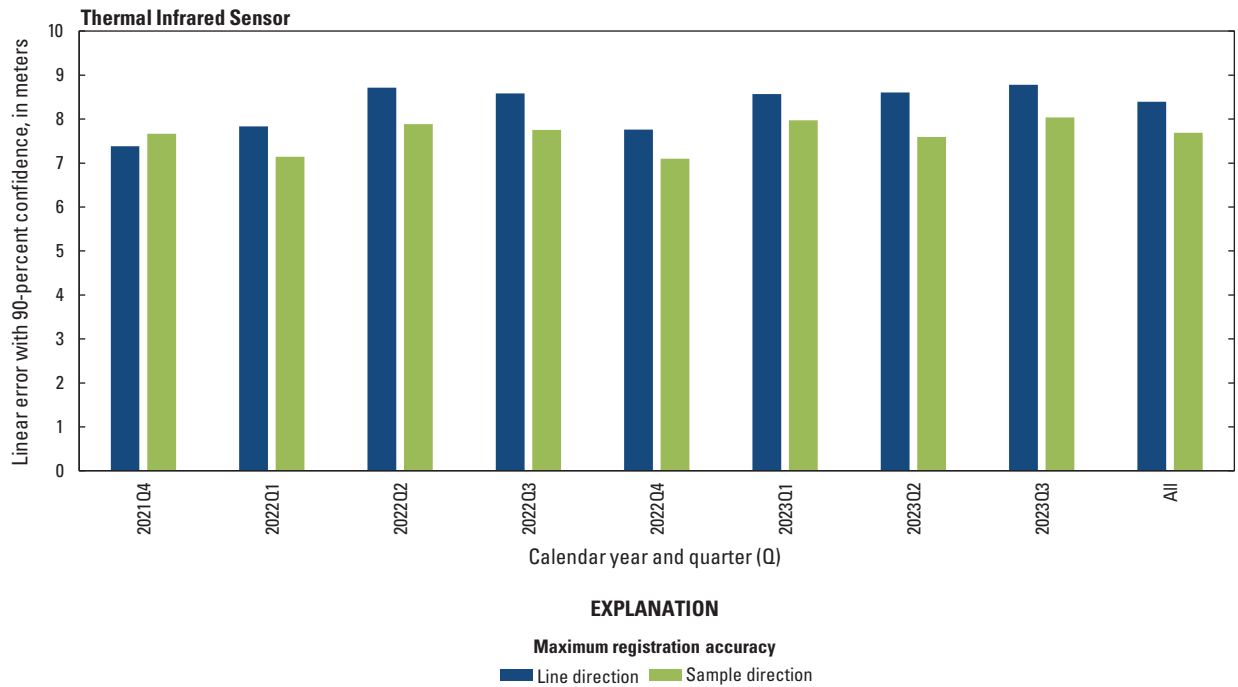


Figure 32. Landsat 9 Thermal Infrared Sensor lifetime band registration accuracy by quarter.

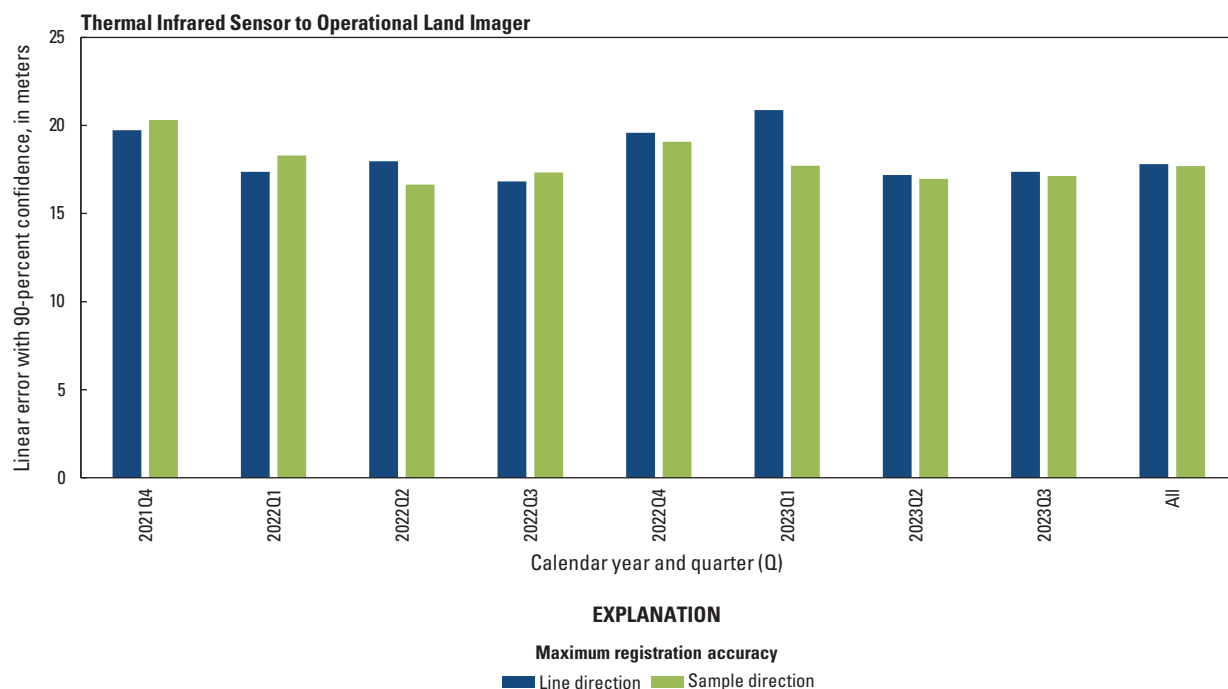


Figure 33. Landsat 9 Thermal Infrared Sensor to Operational Land Imager lifetime band (excluding cirrus) registration accuracy by quarter.

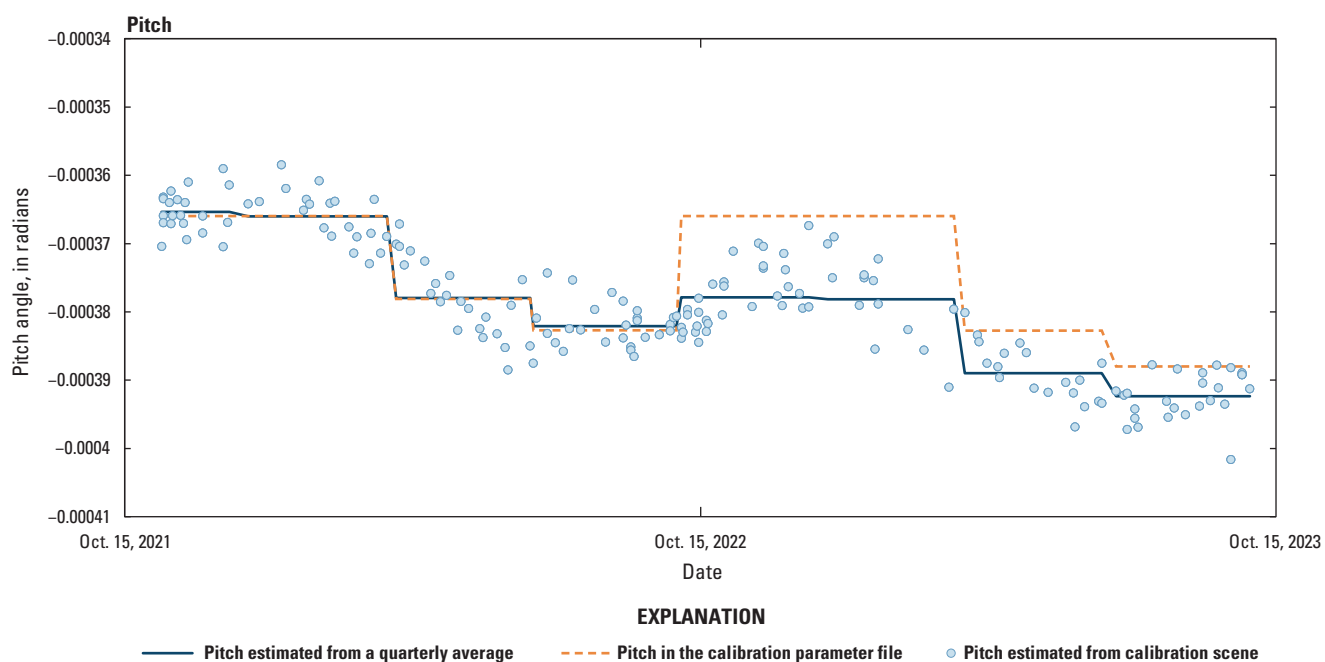


Figure 34. Landsat 9 Thermal Infrared Sensor to Operational Land Imager lifetime pitch alignment.

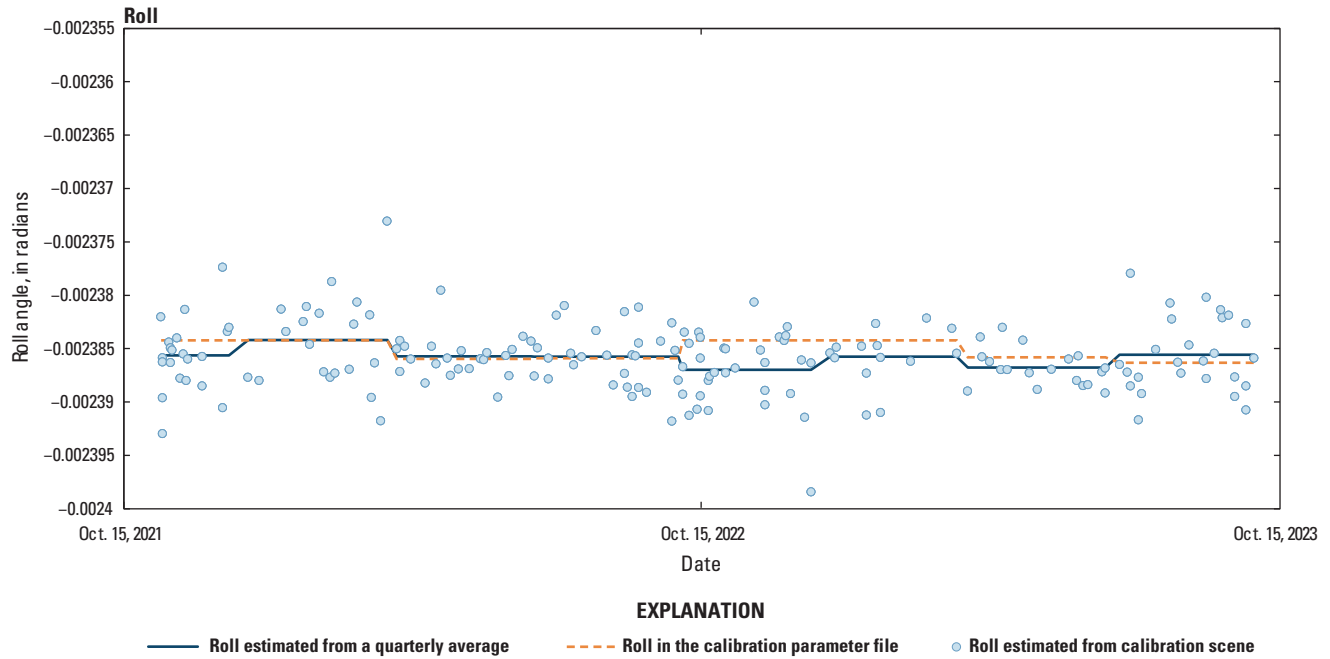


Figure 35. Landsat 9 Thermal Infrared Sensor to Operational Land Imager lifetime roll alignment.

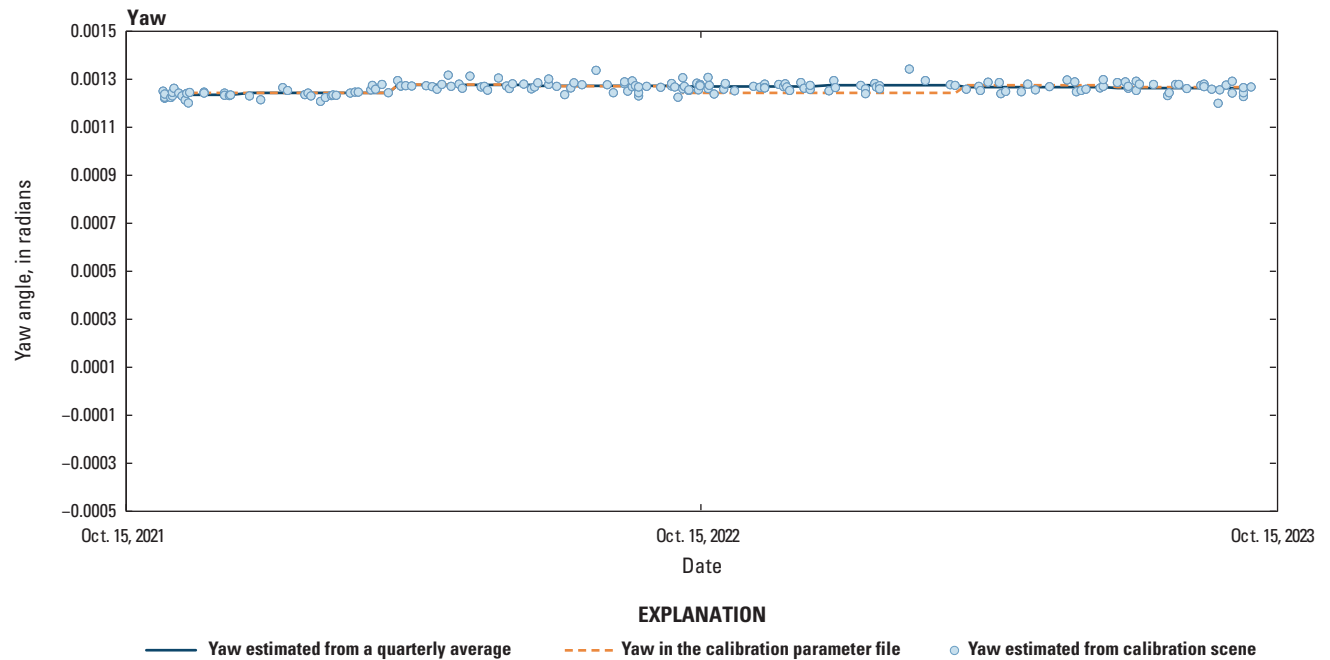


Figure 36. Landsat 9 Thermal Infrared Sensor to Operational Land Imager lifetime yaw alignment.

represents one calibration scene, the dark blue solid lines indicate quarterly alignment averages, and the orange dashed lines indicate applied Collection 2 CPF correction values.

Landsat 9 Geometric Accuracy

The Landsat 9 geometric assessment evaluates the absolute positional accuracy of the image products with respect to a ground (geometric) reference. The geometric accuracy assessment estimates the geometric error between the L1TP products and GCPs using automated cross-correlation techniques (USGS, 2021d).

Based on analysis results, relative accuracy of the Collection 2 GCPs is comparable to the digital orthophoto quadrangle (DOQ) supersites, which are sites created from a mosaic of highly accurate high-resolution terrain-corrected aerial data. Comparatively, relative accuracy of the Collection 2 GCPs is substantially better than the internal consistency of the Collection 1 GCPs. Overall, results based on cloud-contaminated scenes are the primary contributor to poor geometric accuracy from L1TP products. Lifetime quarterly geometric accuracy at a circular error with 90-percent confidence (CE90) is shown in figure 37. Blue bars indicate the geometric accuracy estimated over DOQ supersite paths/rows (calibration sites) with cloud-free scenes, yellow bars indicate geometric accuracy estimated over supersite paths/rows with no cloud constraints using Collection 2 GCPs, and green bars indicate geometric accuracy estimated over all L1TP scenes

processed in Collection 2 using Collection 2 GCPs with no cloud constraints. All results for this quarter are within the accuracy specification.

Lifetime and quarter 3, 2023, geometric accuracies for L1TP products are 3.5 and 3.6 meters when compared against cloud-free scenes over supersite paths/rows (using DOQ GCPs), 5.9 and 5.0 meters when compared against all L1TP scenes over supersite paths/rows only, and 11.0 and 8.4 meters when analyzing all the L1TP scenes processed in Collection 2, respectively. Note that seasonal effect is a factor in accuracy results.

Landsat 9 Geodetic Accuracy

The purpose of the geodetic accuracy assessment is to ensure that the Landsat 9 L0Rp data can be successfully processed into L1 systematic products that meet the system requirement of 65 meters at a CE90 horizontal accuracy. To measure the accuracy, calibration scenes are automatically correlated with data from the panchromatic band to measure the discrepancy between the known ground location and the position predicted by the OLI geometric model (USGS, 2021d).

Based on analysis results, absolute accuracy of the Collection 2 GCPs is comparable to the DOQ supersites and is substantially better compared to the Collection 1 GCPs (Rengarajan and others, 2020). Lifetime quarterly geodetic accuracy (CE90) is shown in figure 38. Blue bars indicate the accuracy estimated using DOQ supersite paths/rows (calibration site), and green bars indicate accuracy estimated from

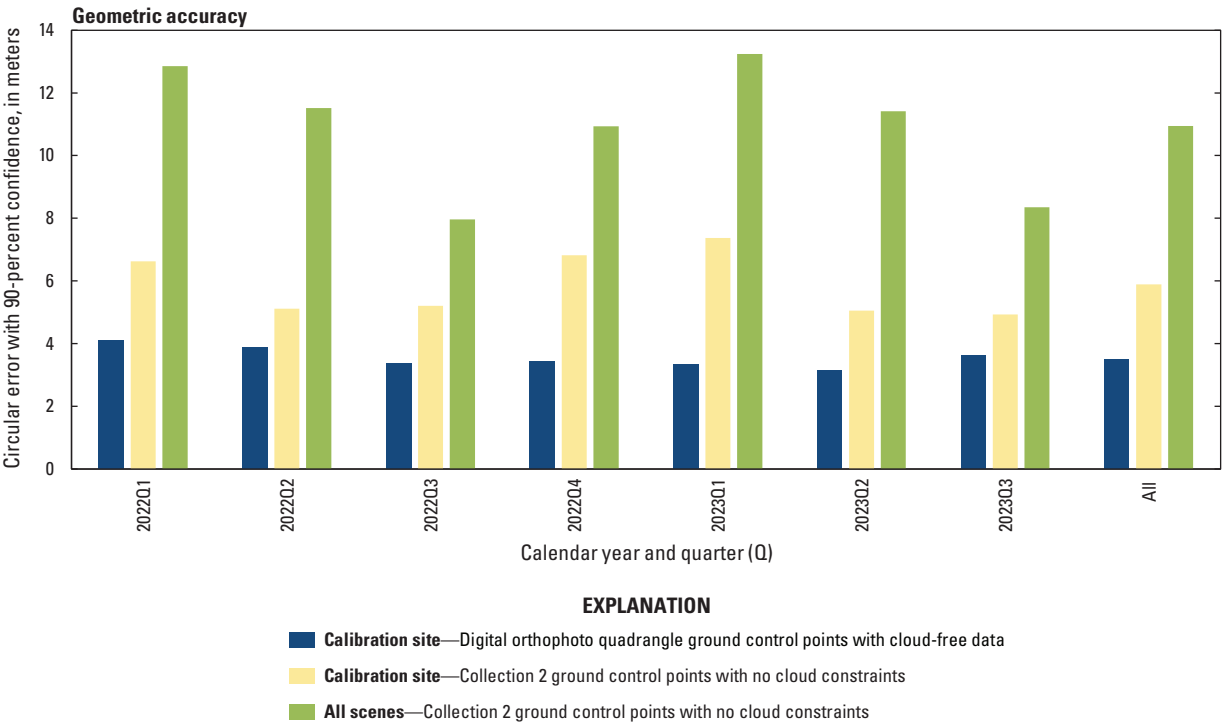


Figure 37. Landsat 9 lifetime geometric accuracy by quarter.

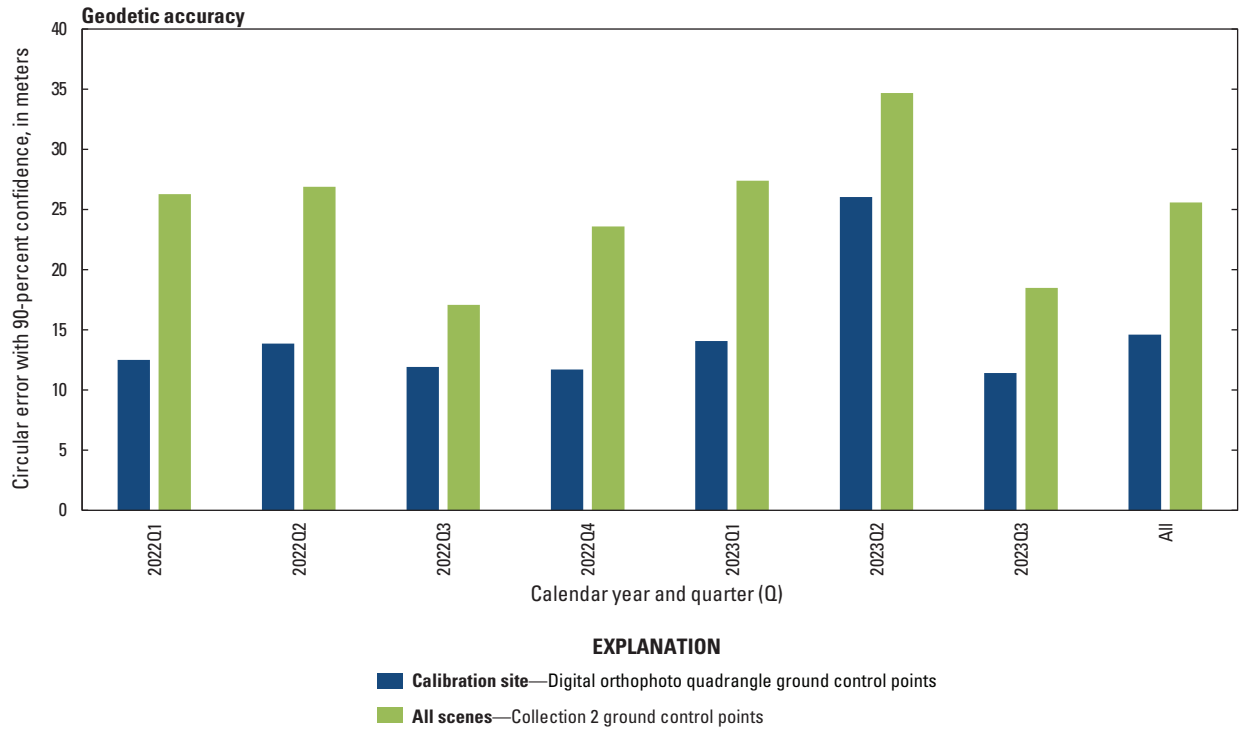


Figure 38. Landsat 9 lifetime geodetic accuracy by quarter.

all L1TP scenes processed in Collection 2 using Collection 2 GCPs. As in the case with the geometric accuracy, a wide variety of scene types (cloud contaminated, islands, desert, snow covered, ice sheets, and so on) are the primary contributor to the poor geodetic accuracy for Collection 2 GCP-based results.

Lifetime geodetic accuracies for systematic products are 14.6 meters when compared using DOQ GCPs over supersites and 25.6 meters when compared using Collection 2 GCPs over all the scenes processed in Collection 2, respectively.

Landsat 9 to Landsat 8 Operational Land Imager Geometric Coregistration

The Landsat 9 and Landsat 8 OLI sensors provide identical spectral and spatial characteristics. To measure the geometric coregistration, image-to-image comparisons between

Landsat 9 and Landsat 8 L1TP products were assessed and the results are shown in [figure 39](#). The image-to-image registration accuracy characterization is performed between panchromatic band image products using a correlation-based mensuration process (Choate and others, 2022). While measuring the image-to-image registration between two sensors, scene pairs were selected in such a way that temporal distance between the two scenes was no more than 32 days. The observed coregistration error between Landsat 9 and Landsat 8 L1TP products is indicated with the magenta dots. Based on analysis results, the Landsat 9 and Landsat 8 L1TP products are well coregistered to within 3 meters of the CE90 (Rengarajan and others, 2024).

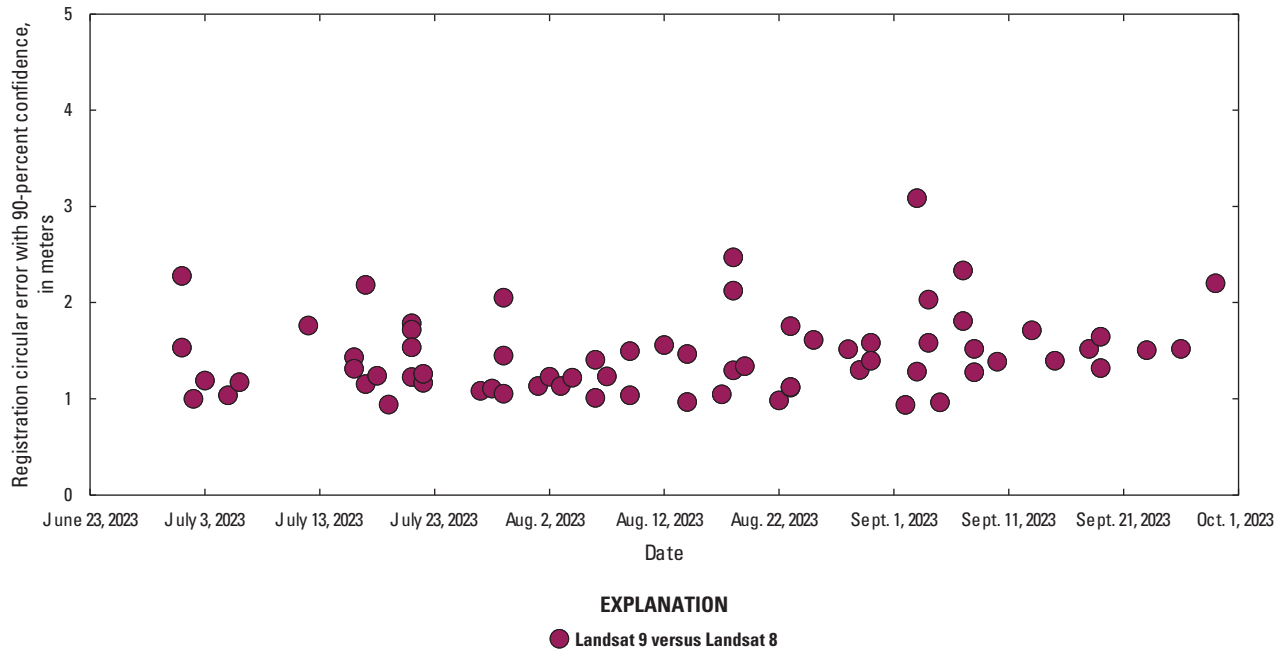


Figure 39. Coregistration error between Landsat 9 and Landsat 8 Level 1 terrain-corrected products, quarter 3, 2023.

Landsat 8 Radiometric Performance Summary

The Landsat 8 on-orbit radiometric performance for this reporting quarter (quarter 3, July–September 2023) meets all requirements as outlined in USGS (2019b). The quarterly OLI and TIRS radiometric performance summaries are provided in [tables 5](#) and [6](#), respectively.

Landsat 8 Operational Land Imager Signal-to-Noise Ratio

The SNR for each of the OLI spectral bands is characterized at a prescribed band-specific $L_{typical}$ level, as described in [table 3](#). The SNR of a detector at a given radiance level is defined as the mean of the measured pixel radiances acquired over a homogenous target divided by their standard deviation. A curve is fit to the SNR at the measured radiance levels and is evaluated at the prescribed $L_{typical}$ level. The SNR is characterized at multiple stages of the instrument build, culminating in the testing of the fully integrated instrument.

The Landsat 8 OLI SNR is evaluated on orbit each month. It remains consistently two to three times better than requirements and about eight times better than the Landsat 7 ETM+ SNR. The Collection 2 SNR slightly increased because of improvement in the bias calculation, further exceeding requirement thresholds. The per-band OLI median SNR at the $L_{typical}$ level (yellow bars) for September 2023, which for all bands easily exceeds the OLI SNR requirements (blue bars) by

more than 50 percent, is shown in [figure 40](#). Lifetime SNR stability at $L_{typical}$ for each OLI band is represented in [figures 41](#), [42](#), [43](#), [44](#), [45](#), [46](#), [47](#), [48](#), and [49](#); monthly SNR values (for the detectors that have median SNRs for all bands) are denoted by the diamonds, and the uncertainties in the monthly SNR model are denoted by the error bars. The SNR for each band has remained stable over time (within the uncertainty of the models and much greater than the required levels).

Landsat 8 Thermal Infrared Sensor Noise Performance

Noise can be defined as variation in the detected signal over time when observing a stable source of radiation. For thermal sensors, noise is usually expressed in terms of a change in brightness temperature (that is, $NE\Delta T$). $NE\Delta T$ is estimated as the standard deviation of detector data acquired over a uniform radiance source and then converted to temperature. Noise performance is completed on blackbody and deep space TIRS data (Montanaro and others, 2014).

All Landsat 8 TIRS detectors have similar $NE\Delta T$. At 300 K, band-average noise performance for both thermal bands is about eight times better than the requirement (less than 0.4 K) and about four times better than the $NE\Delta T$ of the Landsat 7 ETM+ thermal band at that same temperature. Lifetime averages of $NE\Delta T$ at 300 K for TIRS band 10 are shown in [figure 50](#), and the same averages for TIRS band 11 are shown in [figure 51](#). In both figures, colored diamonds are used to indicate the observed $NE\Delta T$ values as measured over time.

Table 5. Landsat 8 Operational Land Imager radiometric performance summary, quarter 3 (July–September), 2023.

[The previous quarter is quarter 2 (April–June), 2023. OLI, Operational Land Imager; <, less than; SNR, signal-to-noise ratio; $L_{typical}$, typical radiance; -, not applicable; L_{high} , high radiance; RMS, root mean square; stdev, standard deviation; \leq , less than or equal to; $W/m^2 \text{ sr } \mu\text{m}$, watt per square meter per steradian per micrometer; σ , sigma; spec, specification]

Requirement	Measured value from this quarter	Measured value from previous quarter ¹	Required value	Unit
OLI ghosting	Meets	Meets	Varies	Percent
OLI absolute radiance uncertainty	4	4	<5	Percent
OLI absolute reflectance uncertainty	<3	<3	<3	Percent
OLI median SNR $L_{typical}$	Meets	Meets	Varies	-
OLI median SNR L_{high}	Meets	Meets	Varies	-
OLI uniformity full field of view	0.35	0.35	<0.5	Percent
OLI uniformity banding RMS	0.80	0.80	<1	Percent
OLI uniformity banding stdev	0.15	0.15	<0.25	Percent
OLI uniformity streaking	0.5	0.5	≤ 0.5 , 1	Percent
OLI coherent noise	Meets	Meets	Less than coherent noise threshold curve	-
OLI saturation radiances	Meets	Meets	Varies	$W/m^2 \text{ sr } \mu\text{m}$
OLI 16-day radiometric stability	0.12	0.12	<1	Percent (2σ)
OLI 60-second radiometric stability	0.1	0.1	<0.5	Percent (2σ)
OLI inoperable detectors	0	0	<0.1	Percent
OLI out-of-spec detectors	0.06	0.06	<0.25	Percent

¹From Haque and others (2023b).

Table 6. Landsat 8 Thermal Infrared Sensor radiometric performance summary, quarter 3 (July–September), 2023.

[The previous quarter is quarter 2 (April–June), 2023. TIRS, Thermal Infrared Sensor; \sim , approximately; <, less than; NEAT, noise equivalent change in temperature; K, Kelvin; TBD, to be determined; RMS, root mean square; stdev, standard deviation; -, not applicable; >, greater than; $W/m^2 \text{ sr } \mu\text{m}$, watt per square meter per steradian per micrometer; σ , sigma; spec, specification]

Requirement	Measured value from this quarter	Measured value from previous quarter ¹	Required value	Unit
TIRS absolute radiance uncertainty	~ 1	~ 1	<2	Percent
TIRS NEAT (at 300 K)	0.05	0.05	<0.4	K
TIRS uniformity full field of view	TBD	TBD	<0.5	Percent
TIRS uniformity banding RMS	TBD	TBD	<0.5	Percent
TIRS uniformity banding stdev	TBD	TBD	<0.5	Percent
TIRS uniformity streaking	<0.5	<0.5	<0.5	Percent
TIRS coherent noise	Meets	Meets	Less than coherent noise threshold curve	-
TIRS saturation radiances	28.4, 19.2	28.4, 19.2	>20.5, >17.8	$W/m^2 \text{ sr } \mu\text{m}$
TIRS 40-minute radiometric stability	0.1	0.1	<0.7	Percent (1σ)
TIRS inoperable detectors	0	0	<0.1	Percent
TIRS out-of-spec detectors	0.21	0.21	<0.25	Percent

¹From Haque and others (2023b).

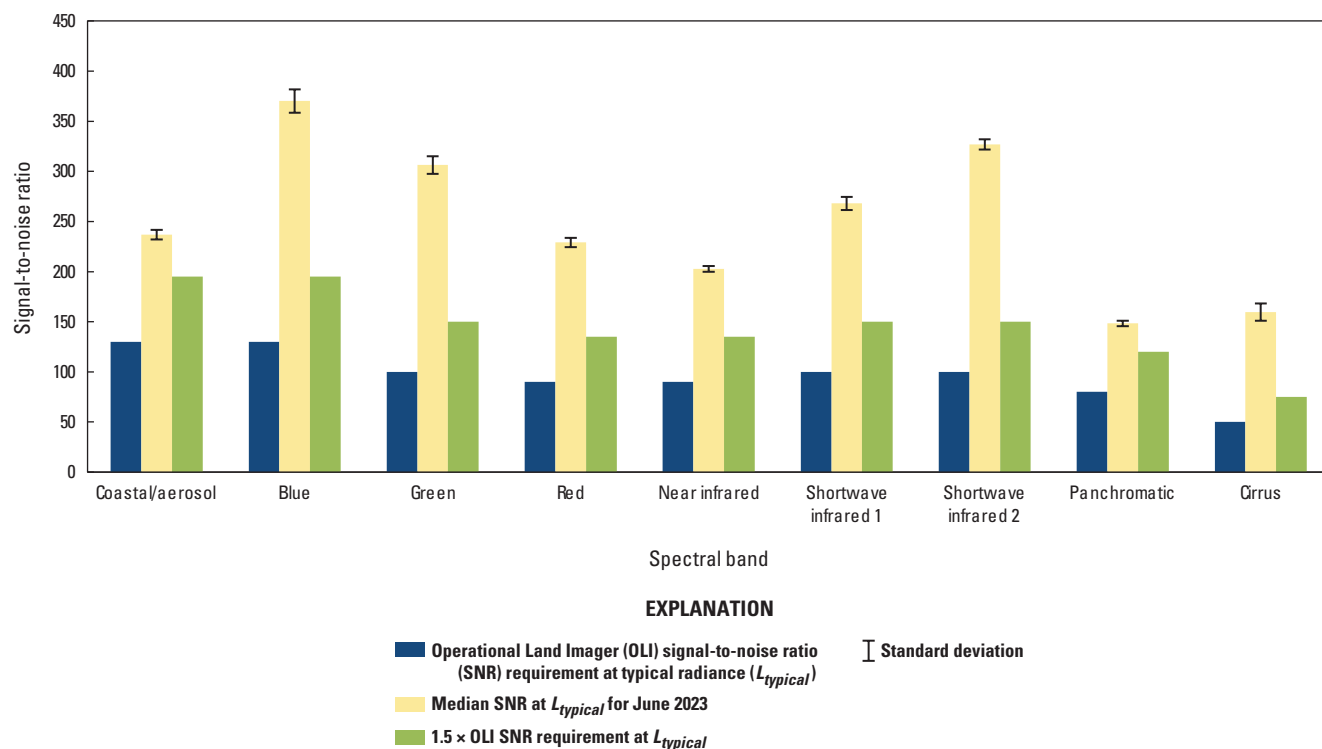


Figure 40. Landsat 8 Operational Land Imager signal-to-noise ratio performance, September 2023.

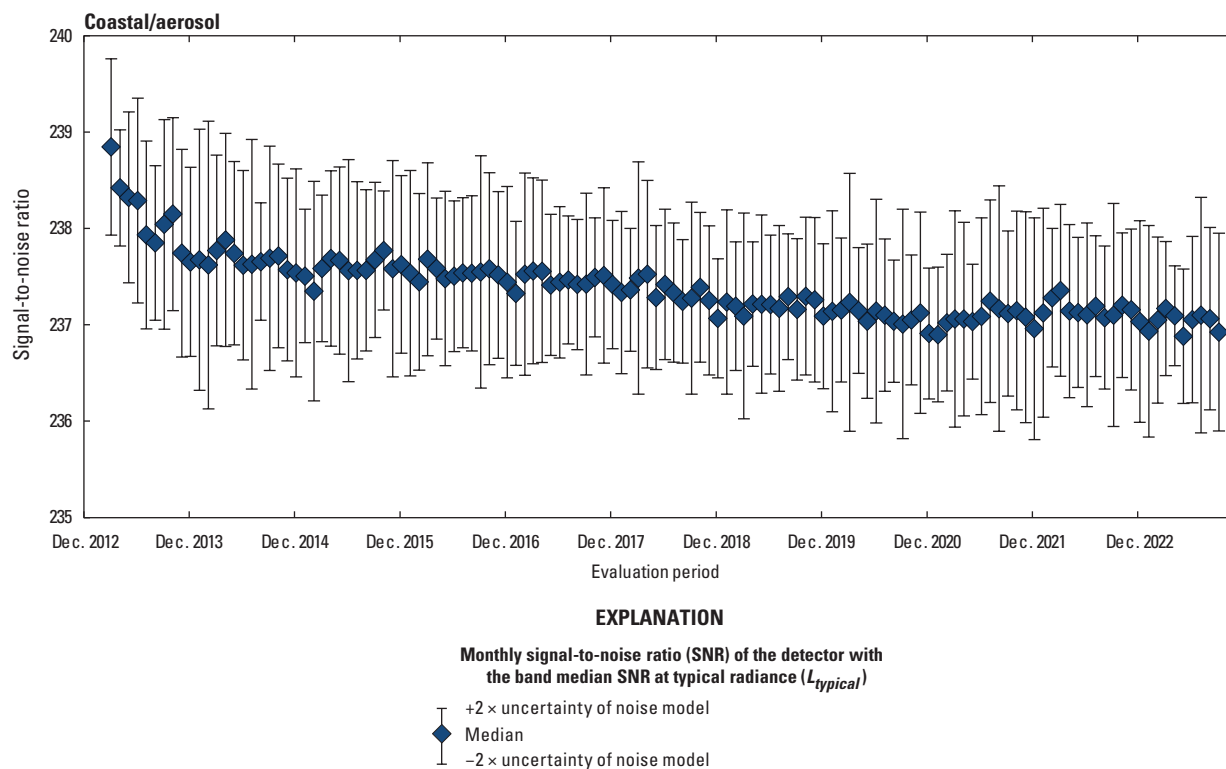


Figure 41. Landsat 8 Operational Land Imager coastal/aerosol band lifetime signal-to-noise ratio stability.

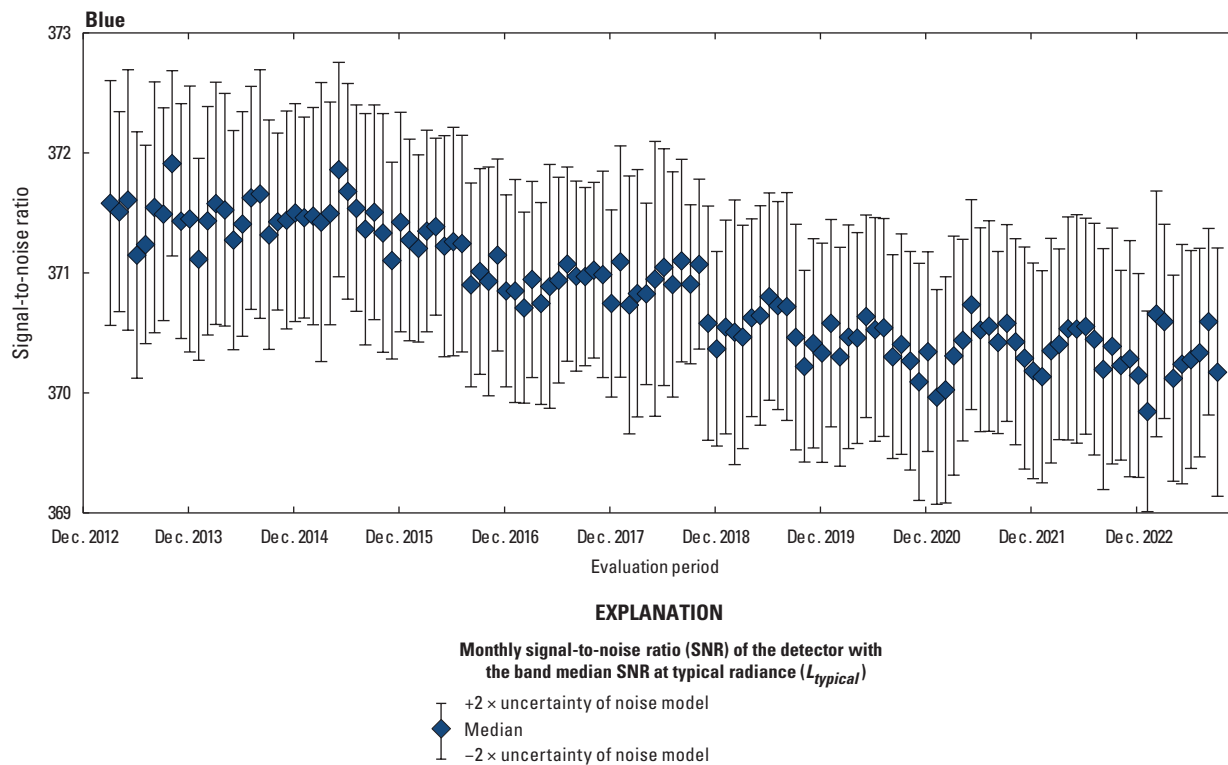


Figure 42. Landsat 8 Operational Land Imager blue band lifetime signal-to-noise ratio stability.

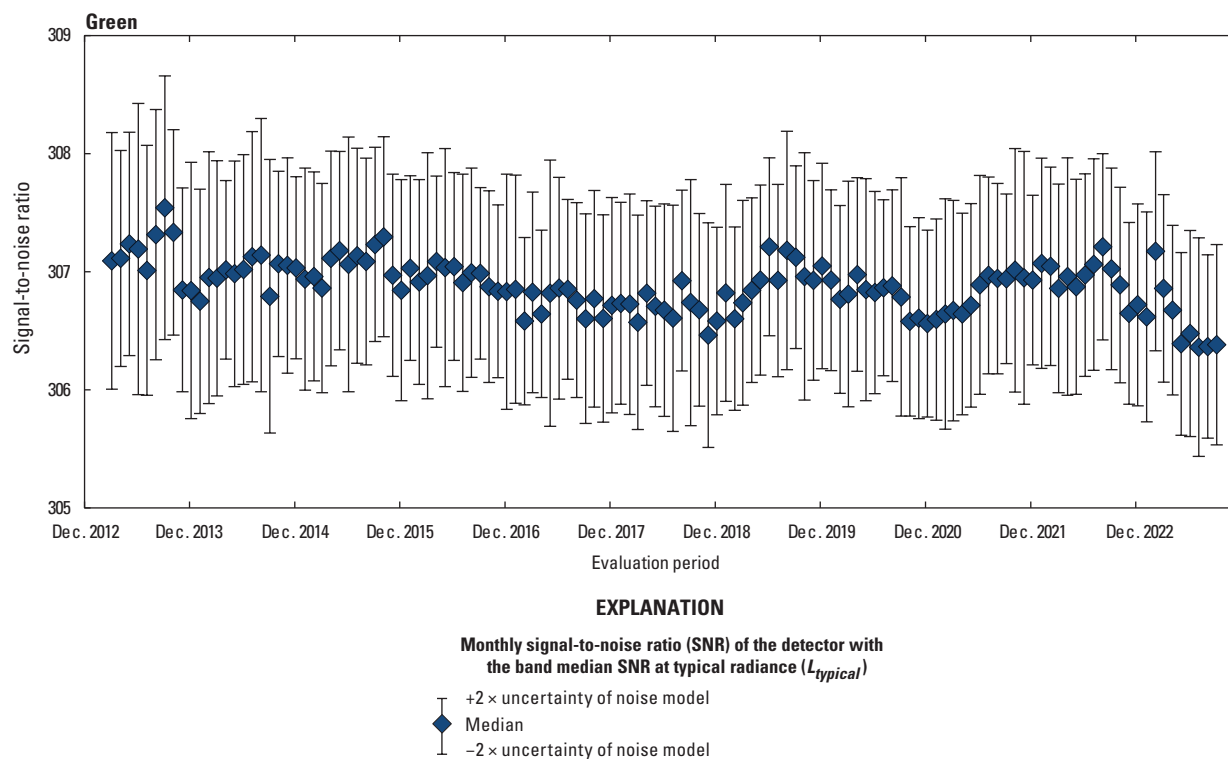


Figure 43. Landsat 8 Operational Land Imager green band lifetime signal-to-noise ratio stability.

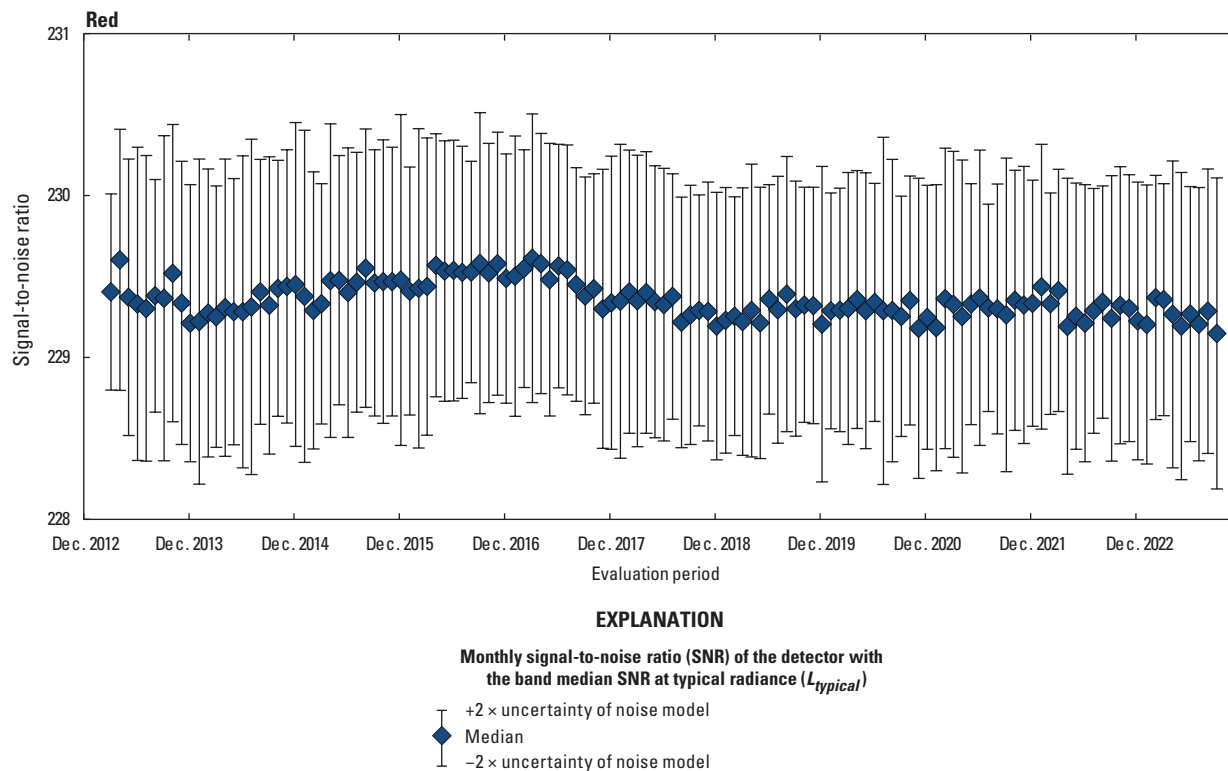


Figure 44. Landsat 8 Operational Land Imager red band lifetime signal-to-noise ratio stability.

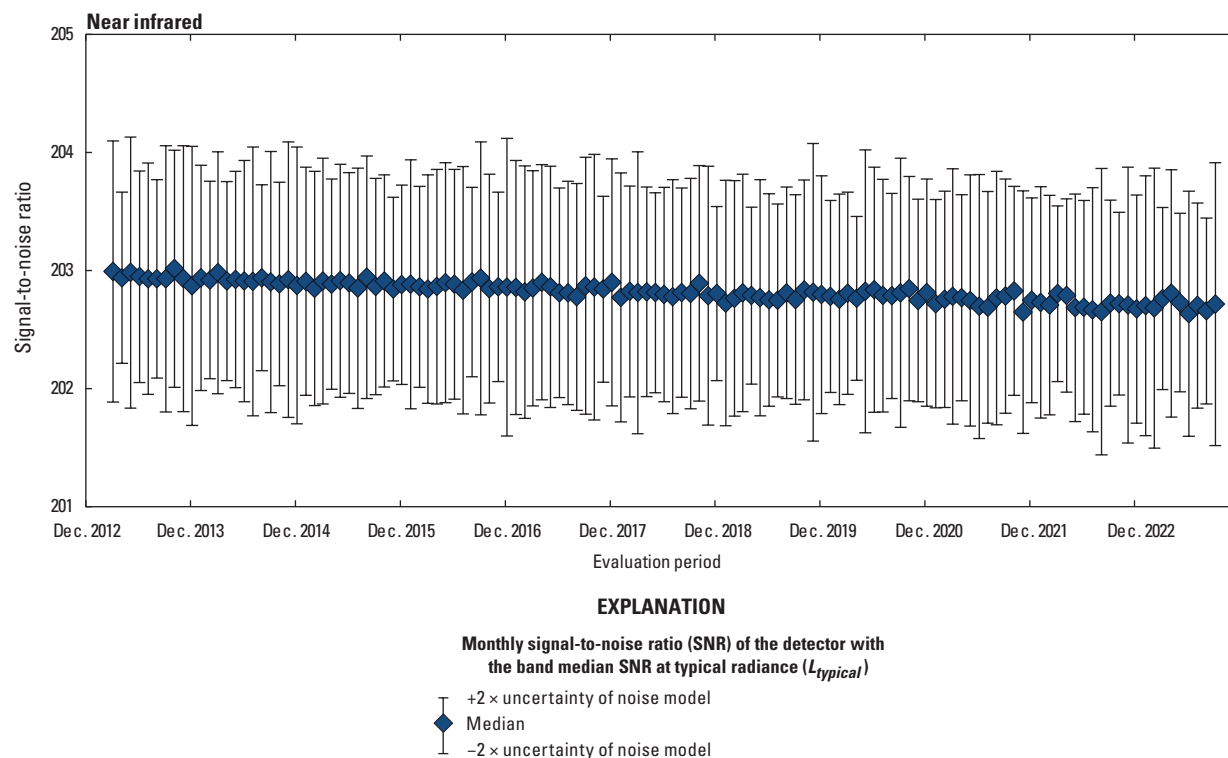


Figure 45. Landsat 8 Operational Land Imager near infrared band lifetime signal-to-noise ratio stability.

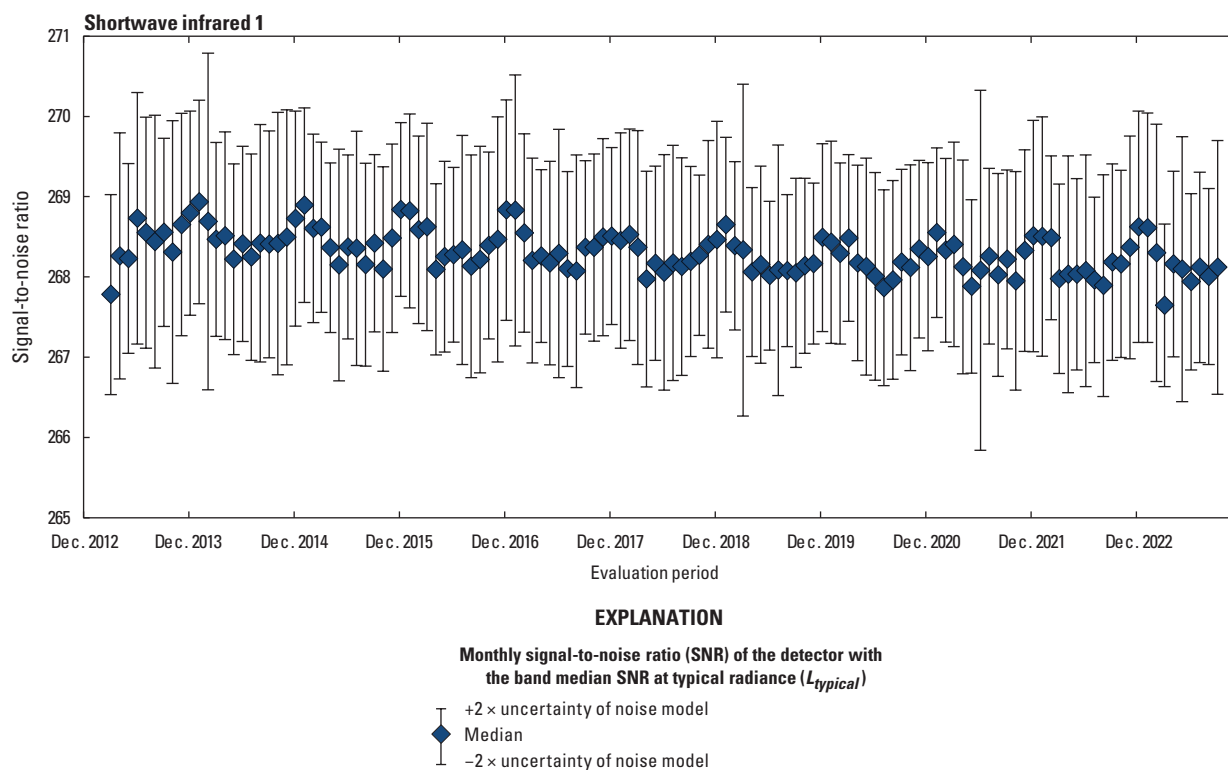


Figure 46. Landsat 8 Operational Land Imager shortwave infrared 1 band lifetime signal-to-noise ratio stability.

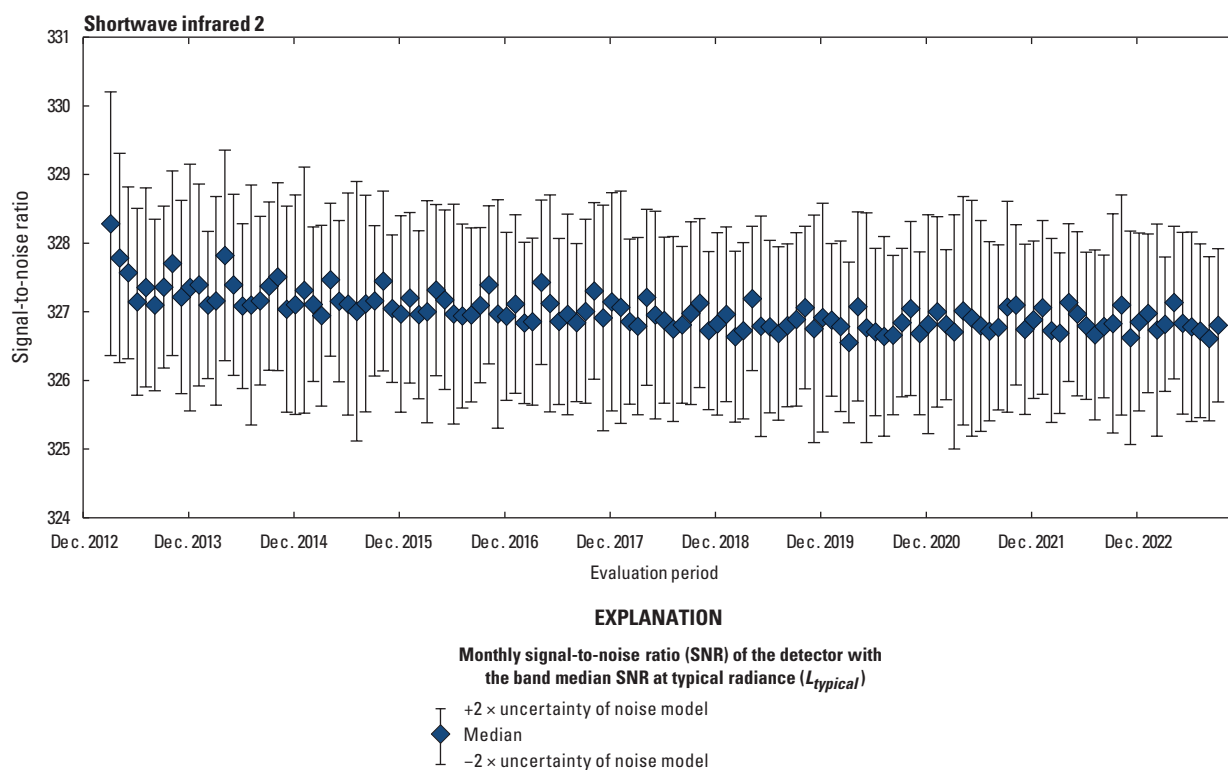


Figure 47. Landsat 8 Operational Land Imager shortwave infrared 2 band lifetime signal-to-noise ratio stability.

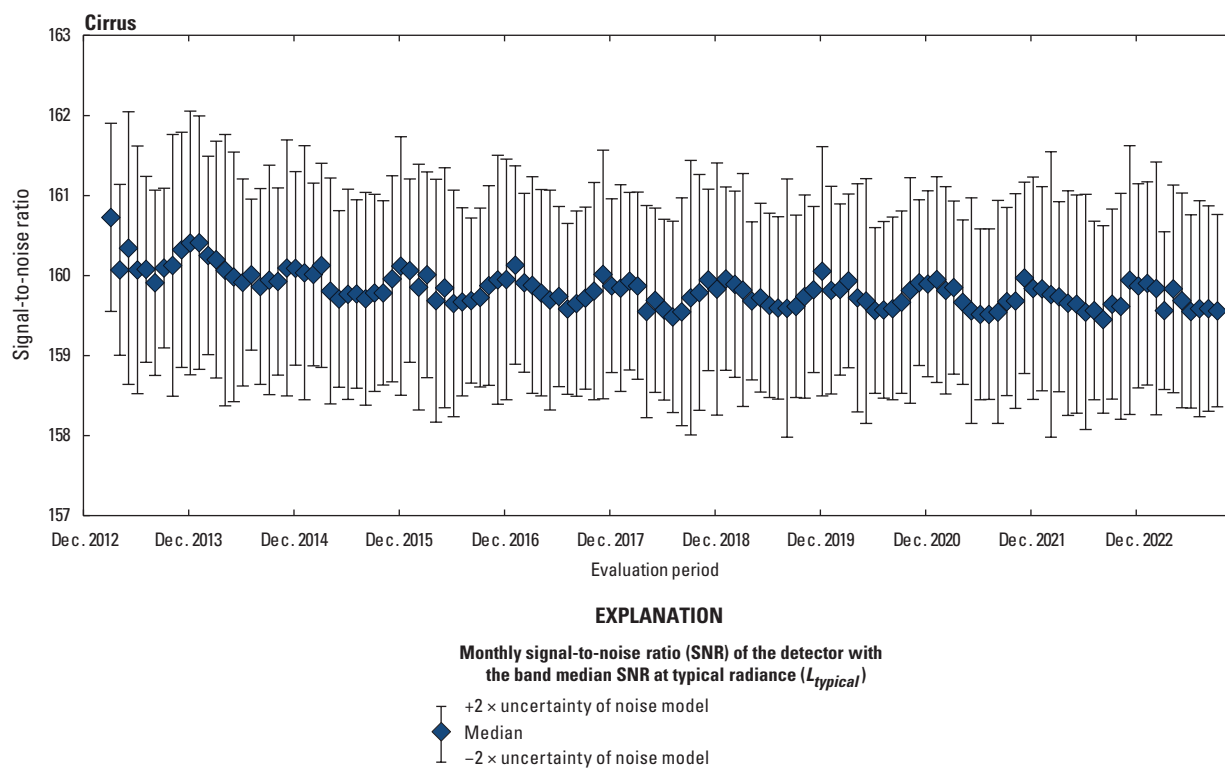


Figure 48. Landsat 8 Operational Land Imager cirrus band lifetime signal-to-noise ratio stability.

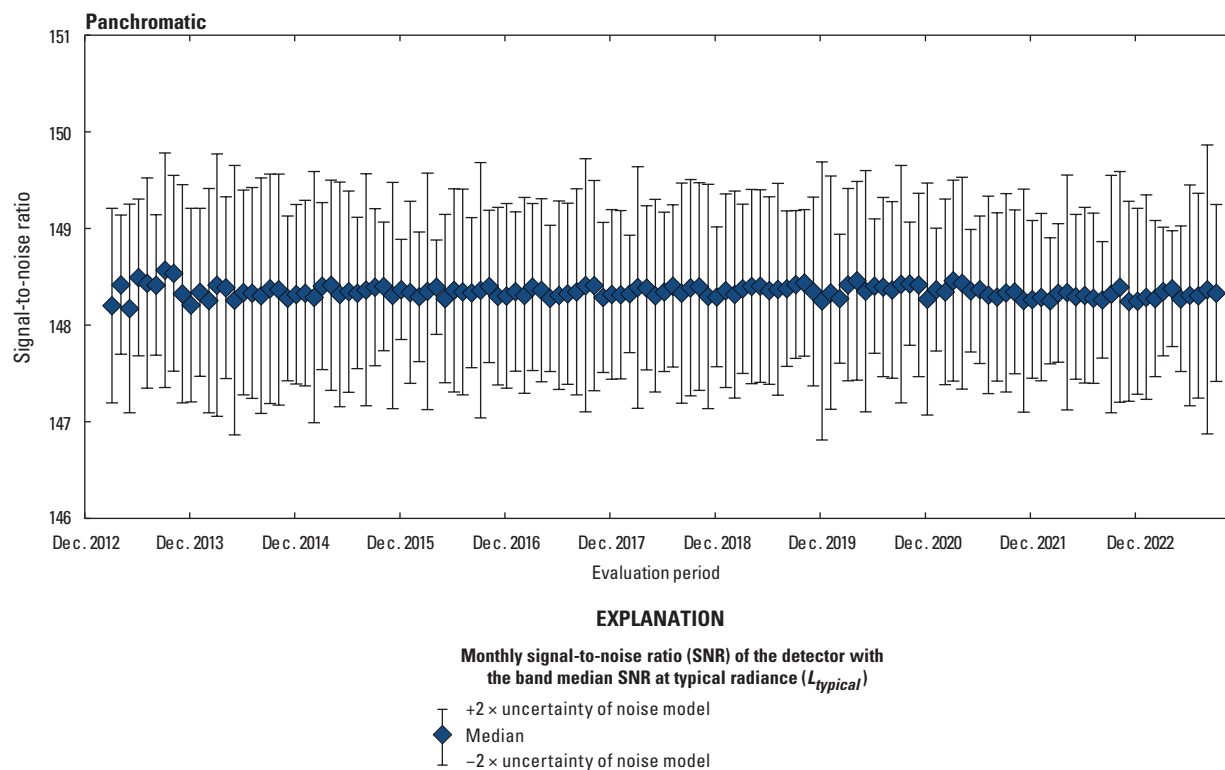


Figure 49. Landsat 8 Operational Land Imager panchromatic band lifetime signal-to-noise ratio stability.

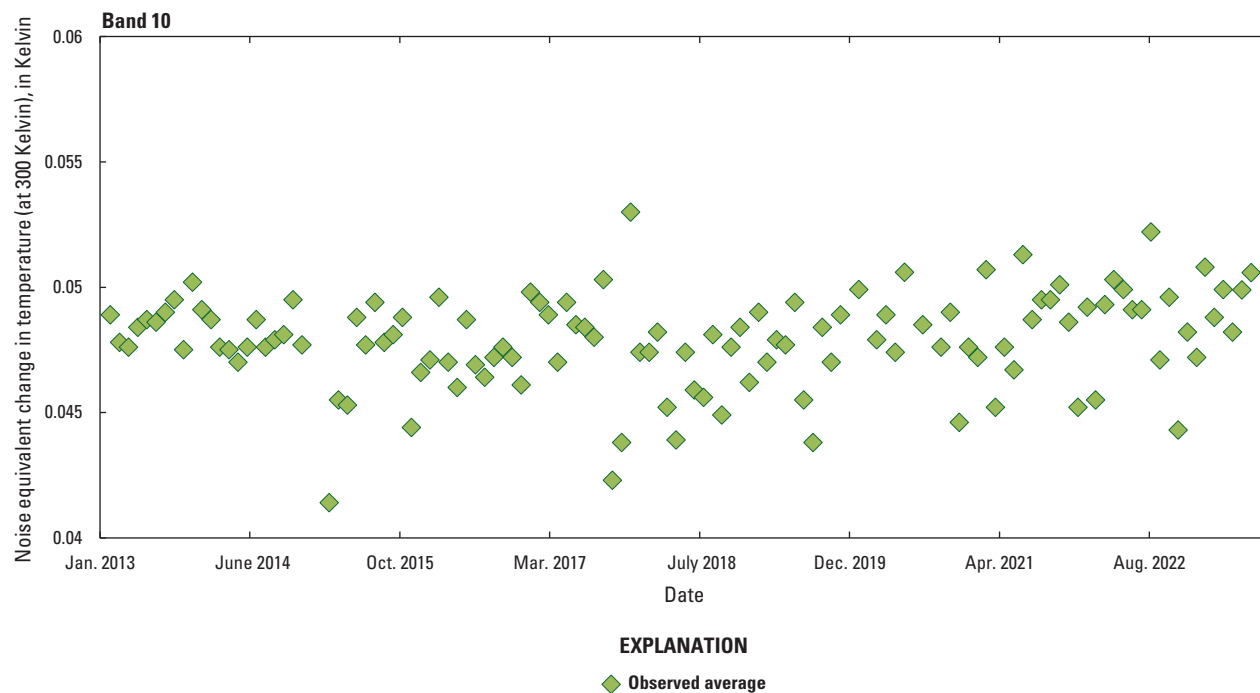


Figure 50. Landsat 8 Thermal Infrared Sensor band 10 lifetime noise performance.

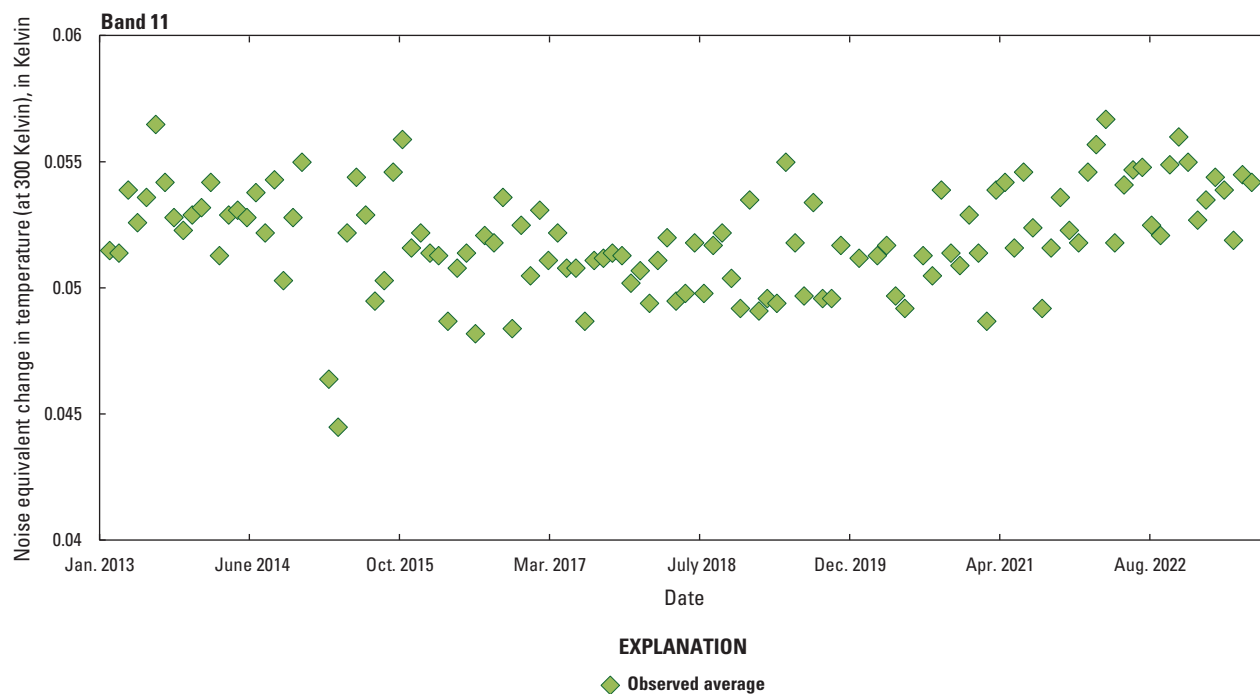


Figure 51. Landsat 8 Thermal Infrared Sensor band 11 lifetime noise performance.

Landsat 8 Radiometric Stability

Radiometric stability of an instrument is fundamental to low uncertainty in the radiometric calibration of data products generated from its measurements. The radiometric response stability is characterized for all OLI and TIRS bands using the instruments' responses to signals from the onboard calibration devices collected over time (USGS, 2021d). The bias and gain stability of an instrument are contributing factors to variability within a radiometrically calibrated product.

The Landsat 8 per-band OLI radiometric stability over the lifetime of the instrument is shown in figures 52, 53, 54, 55, 56, 57, 58, 59, and 60. Within each figure, the x-axis represents years since launch (February 11, 2013), and the y-axis represents the response relative to mission day 75. The solid brown line (figs. 52 and 53) represents the gain model used over time, which is derived from the OLI response to the stimulation lamps, solar panels, and lunar collects; it is only shown for the bands with responsivity (gain) determined to be slowly changing over time (coastal/aerosol [CA] and blue bands). For the remaining bands, response changes were minuscule until the safhold events in November 2020. More information about the Landsat 8 safhold events is available at <https://www.usgs.gov/landsat-missions/november-19-2020-landsat-8-data-availability-update-recent-safhold-events>. These observations indicate high radiometric stability of the instrument over its lifetime. Data derived from bands that have changed responsivity are corrected during product generation, so final products are not affected.

From Micijevic and others (2021), the stability of the Landsat 8 TIRS side A electronics that were used for the first ~700 days of the mission is shown in figures 61 and 62. During that period, TIRS gains changed by about 0.2 and 0.1 percent per year for bands 10 and 11, respectively. These trends reduced on the side B electronics to about 0.05 and 0.01 percent until the two safhold events in November 2020, as seen in figures 63 and 64, respectively. After the safhold events, TIRS responsivity has gradually decreased ~3.0 and ~6.0 percent for bands 10 and 11, respectively. Note that the response degradation is modeled and corrected to within 0.5-percent uncertainty in the L1 products.

Since January 2021, Landsat 8 TIRS onboard calibrator acquisitions have been collected on a weekly basis (instead of once every ~2 weeks) to better monitor the degradation in response observed after the safhold events. Weekly calibration acquisitions are planned into the future if the response degradation trend continues and if geometric and radiometric accuracies are not negatively affected by the increased acquisition frequency.

Landsat 8 Absolute Radiometric Calibration

Absolute radiometric calibration is established on the ground before launch and transferred to orbit using the solar diffuser for OLI and the blackbody for TIRS. Onboard calibrators and PICS (Committee on Earth Observation Satellites, 2021) are used to monitor changes in absolute calibration, and vicarious methods are used to check absolute calibration over

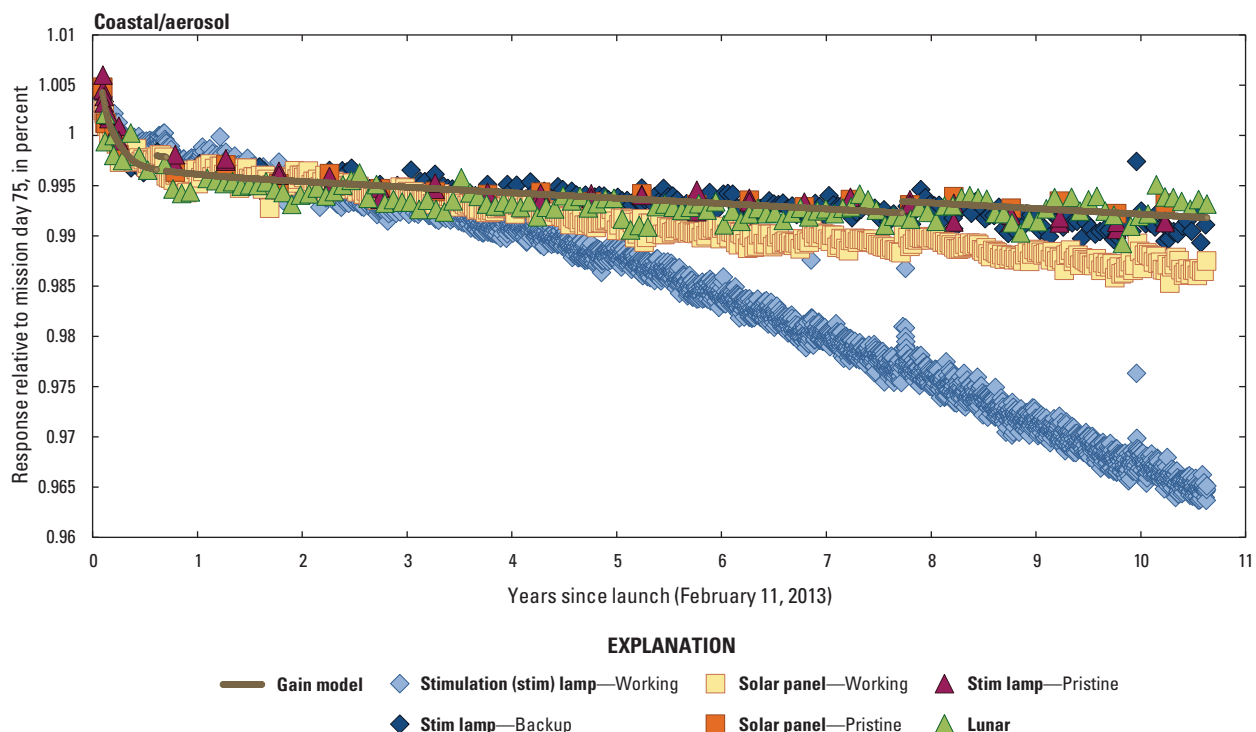


Figure 52. Landsat 8 Operational Land Imager coastal/aerosol band lifetime radiometric stability.

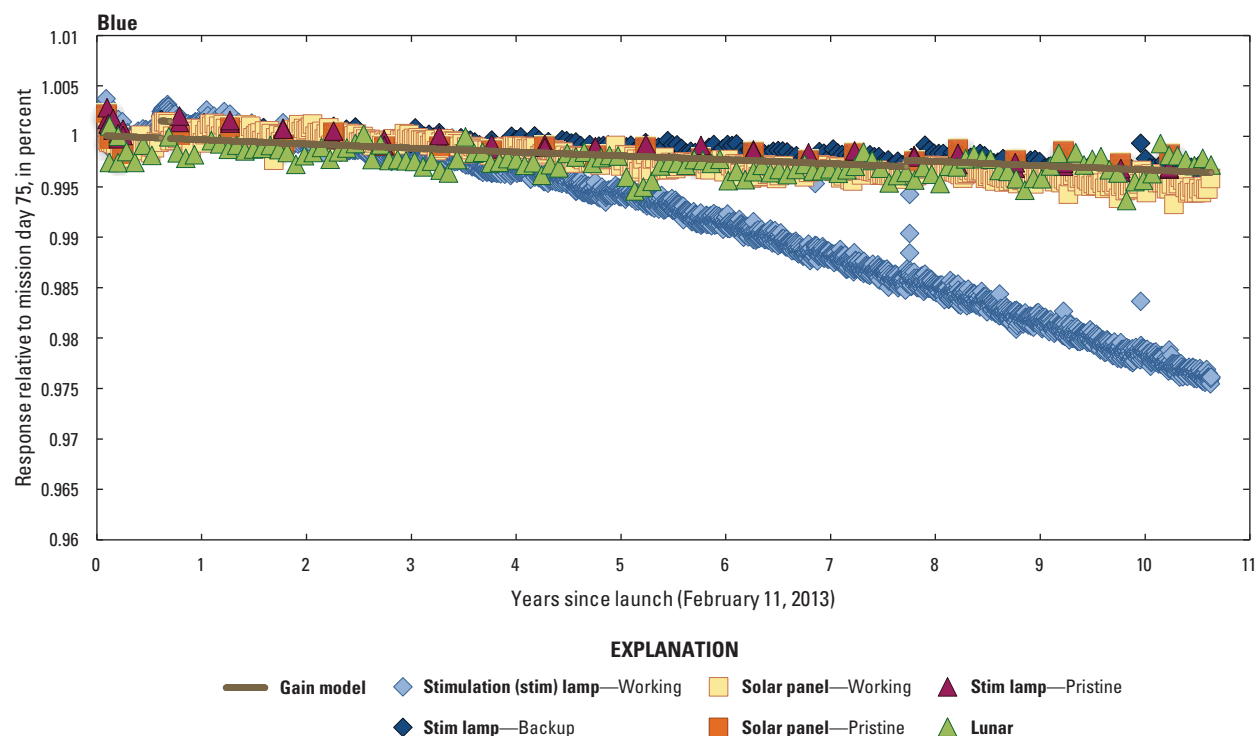


Figure 53. Landsat 8 Operational Land Imager blue band lifetime radiometric stability.

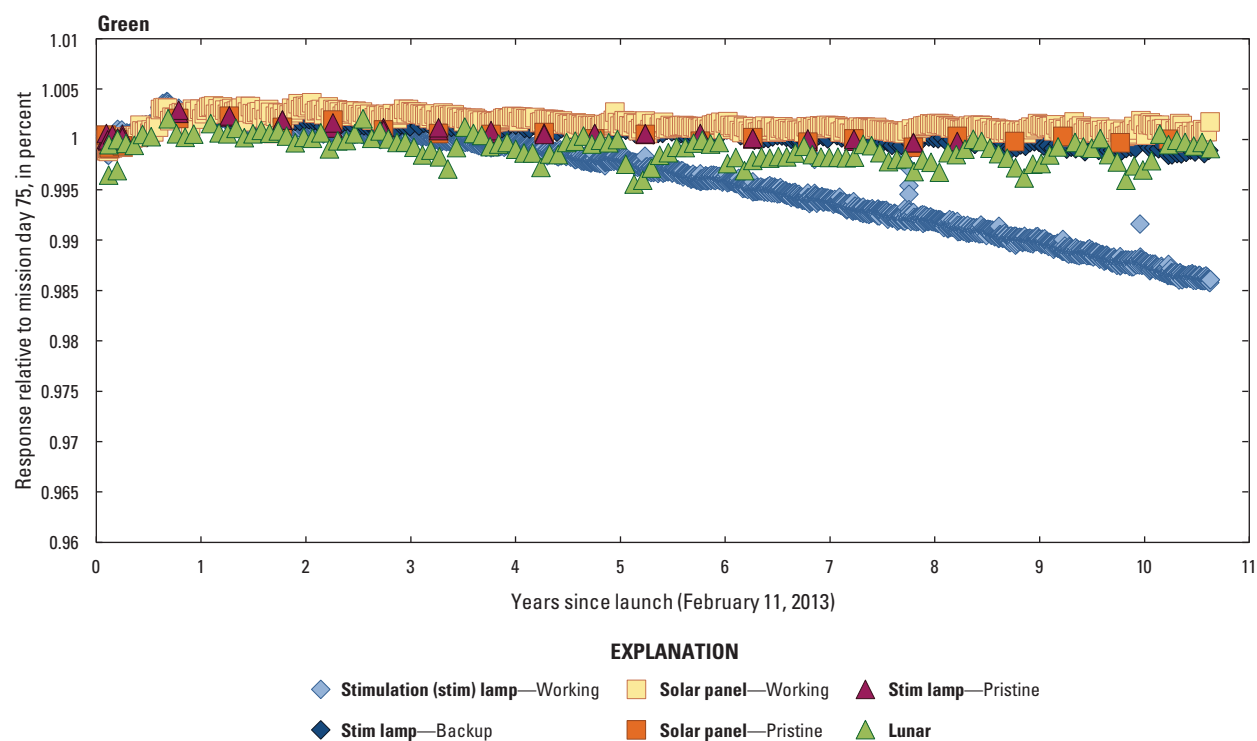


Figure 54. Landsat 8 Operational Land Imager green band lifetime radiometric stability.

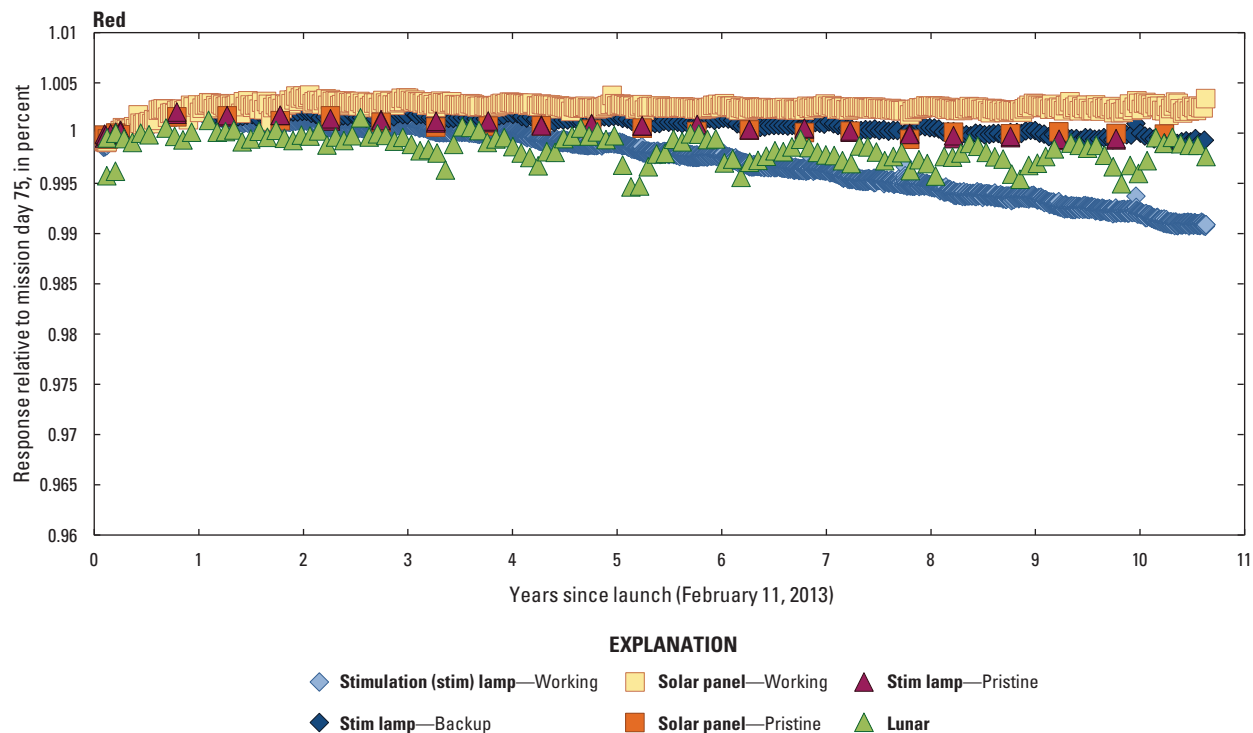


Figure 55. Landsat 8 Operational Land Imager red band lifetime radiometric stability.

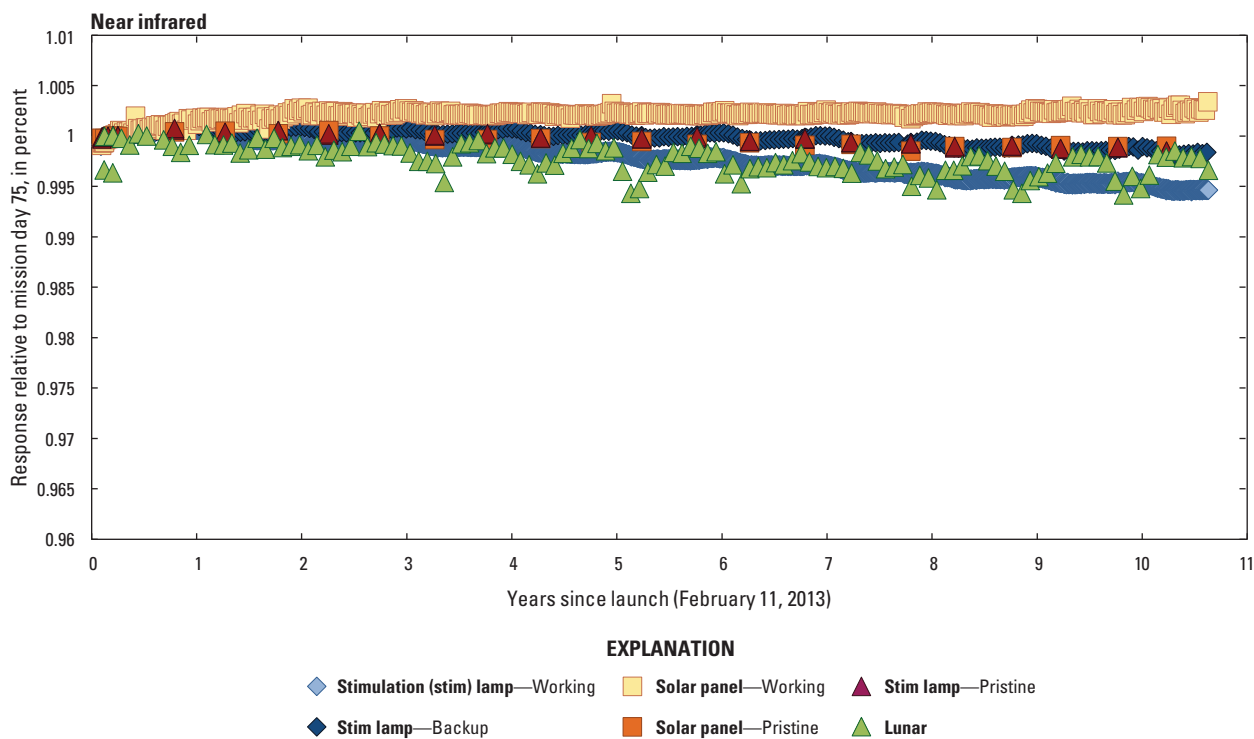


Figure 56. Landsat 8 Operational Land Imager near infrared band lifetime radiometric stability.

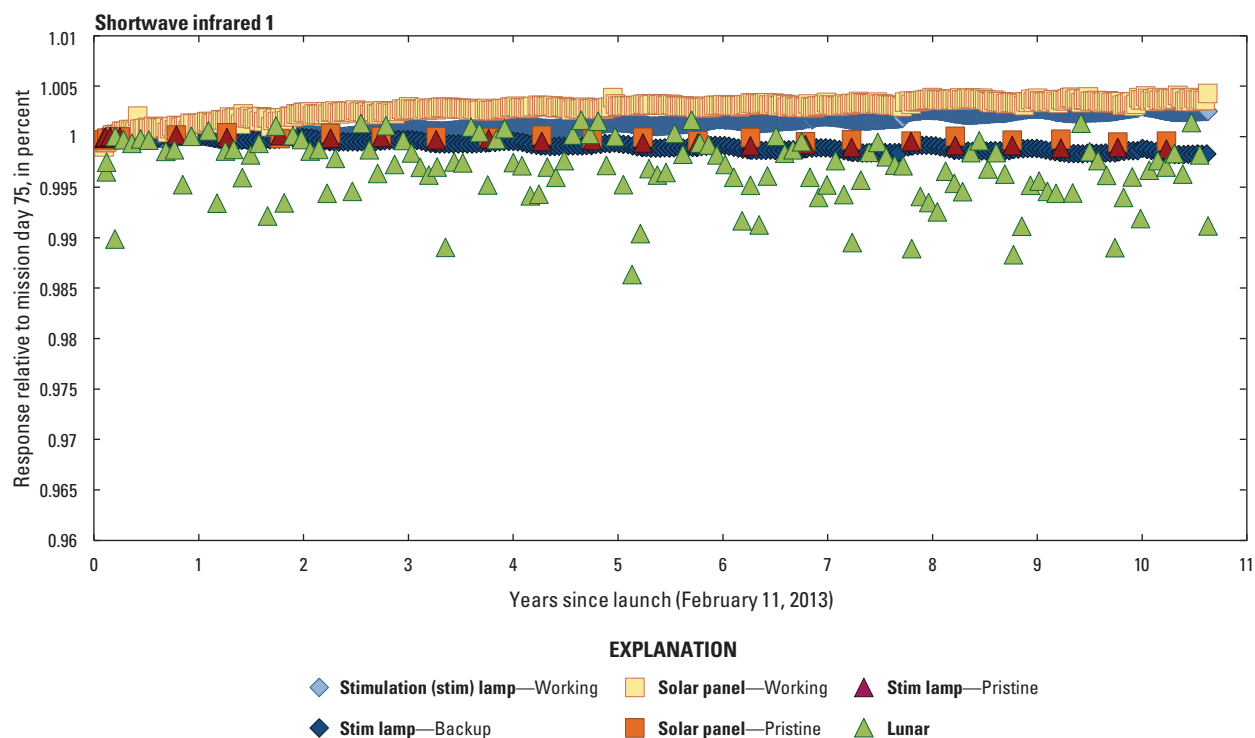


Figure 57. Landsat 8 Operational Land Imager shortwave infrared 1 band lifetime radiometric stability.

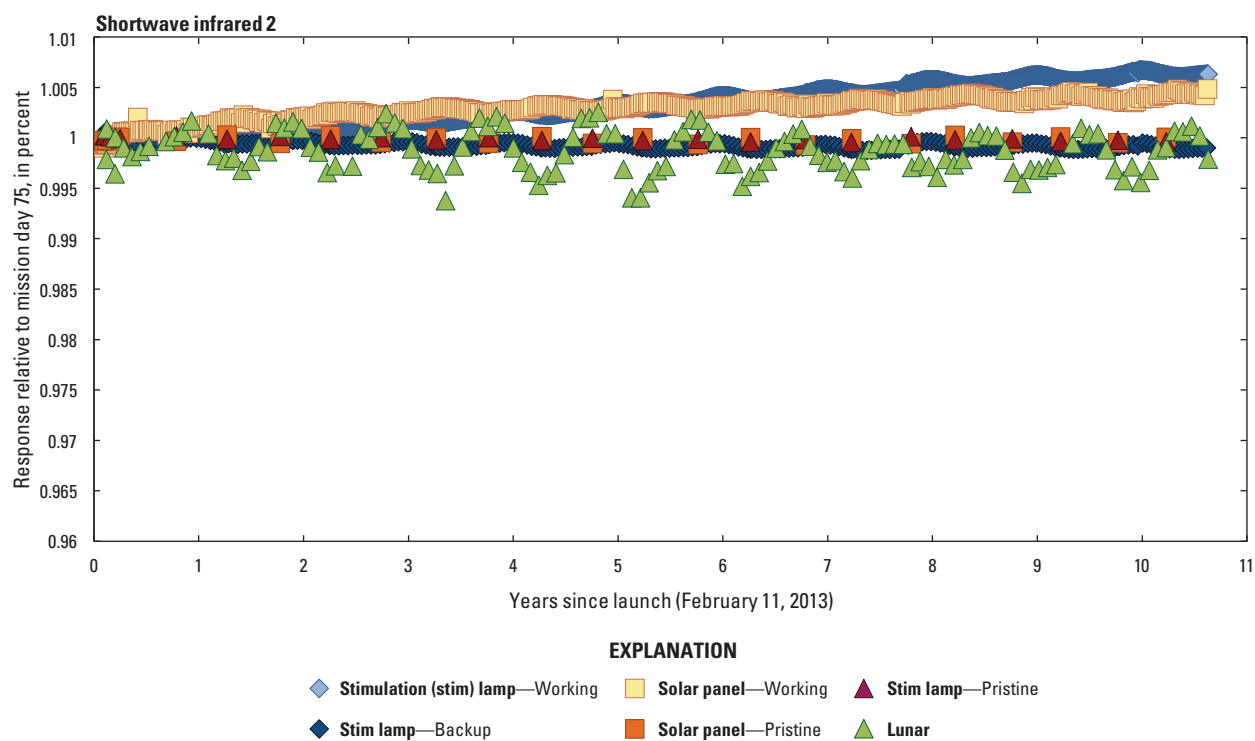


Figure 58. Landsat 8 Operational Land Imager shortwave infrared 2 band lifetime radiometric stability.

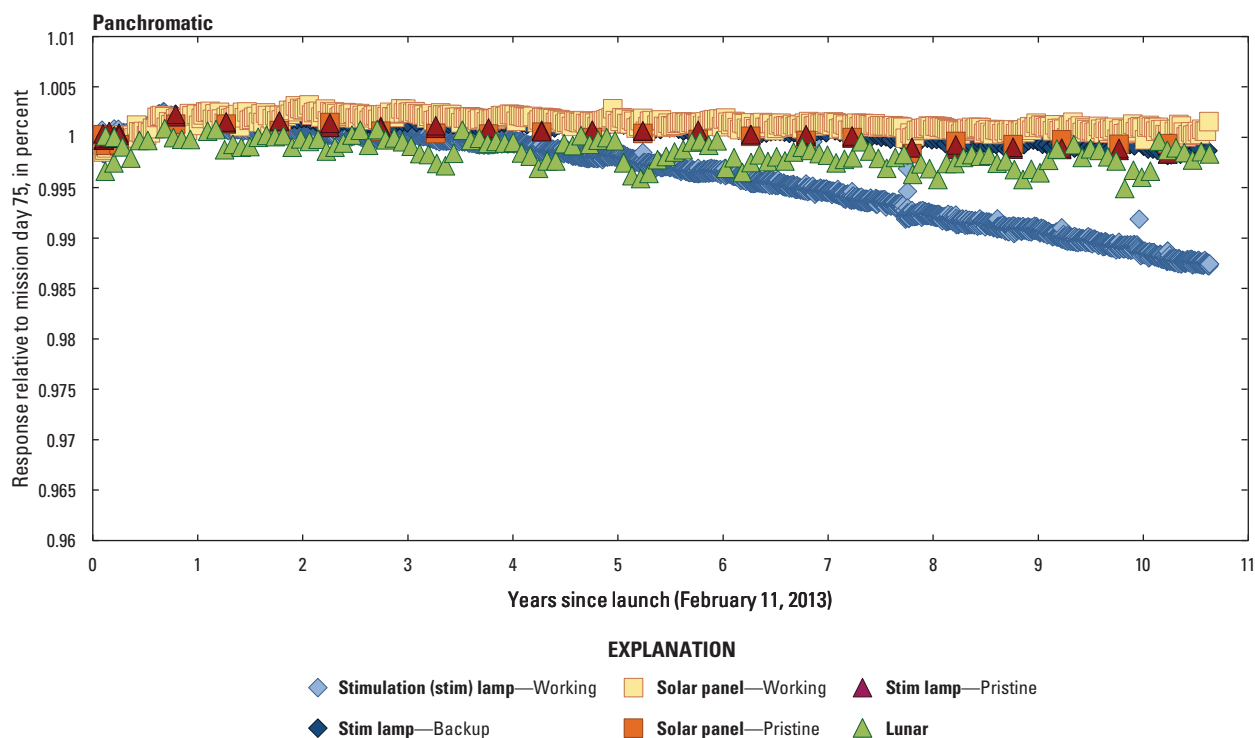


Figure 59. Landsat 8 Operational Land Imager panchromatic band lifetime radiometric stability.

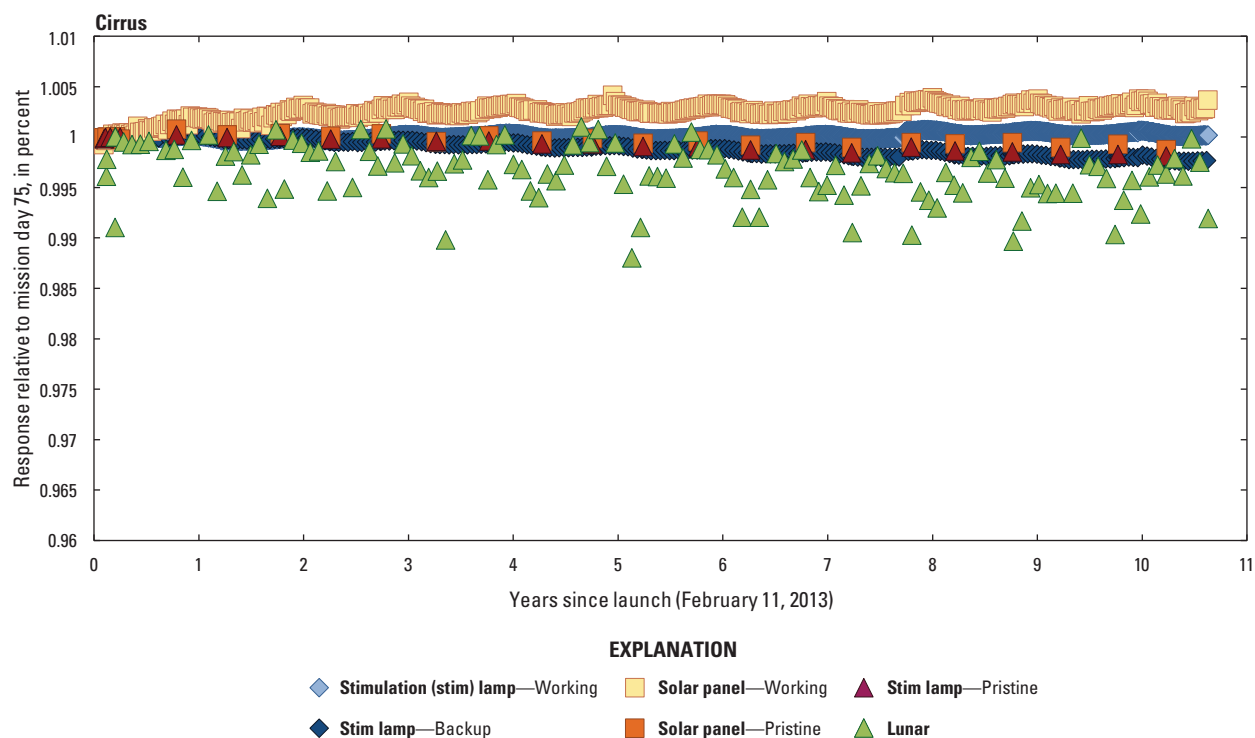


Figure 60. Landsat 8 Operational Land Imager cirrus band lifetime radiometric stability.

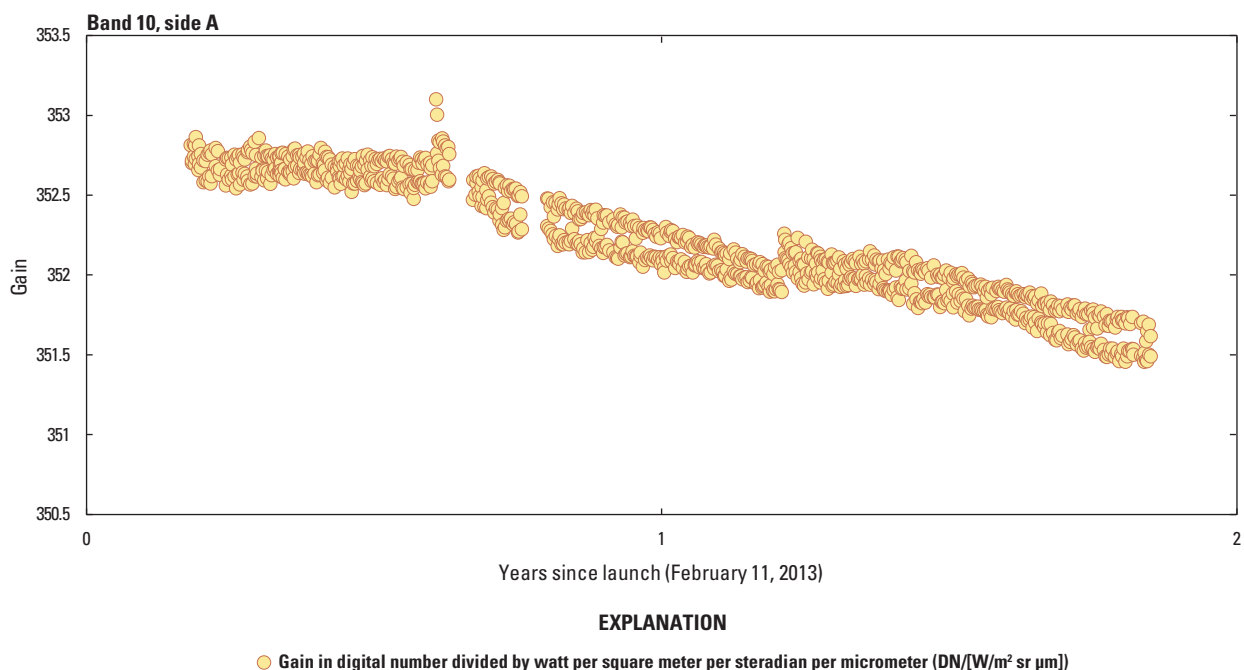


Figure 61. Landsat 8 Thermal Infrared Sensor band 10 radiometric stability (side A).

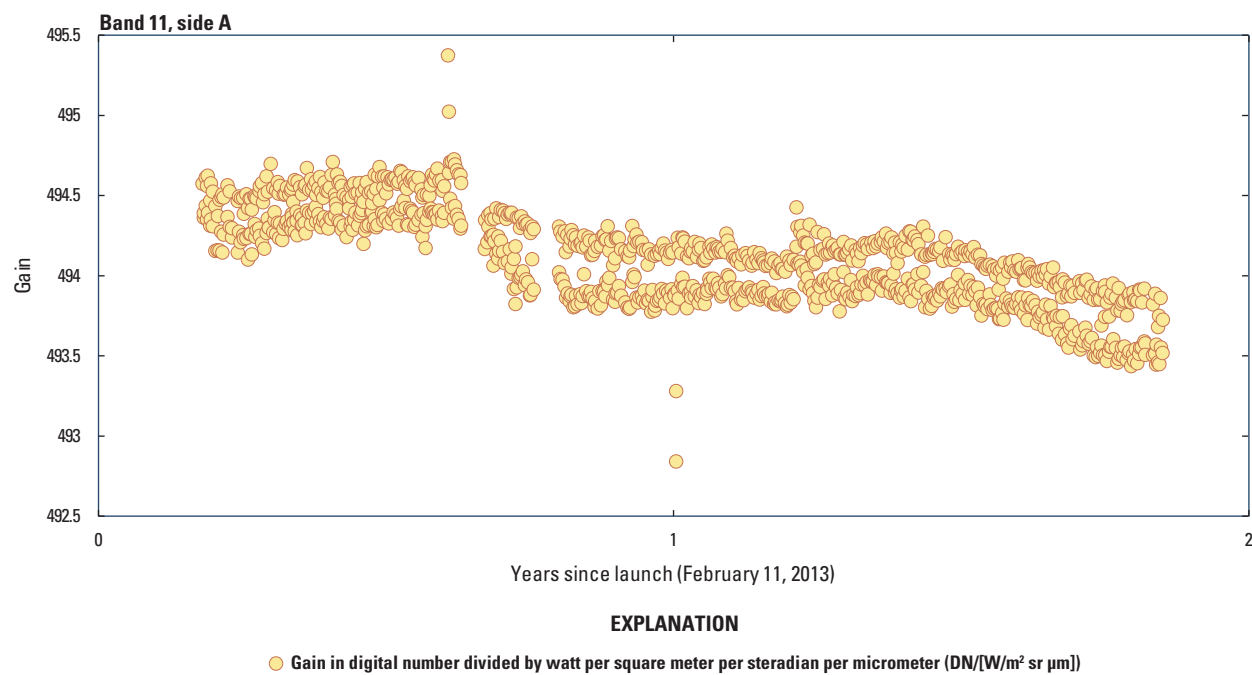


Figure 62. Landsat 8 Thermal Infrared Sensor band 11 radiometric stability (side A).

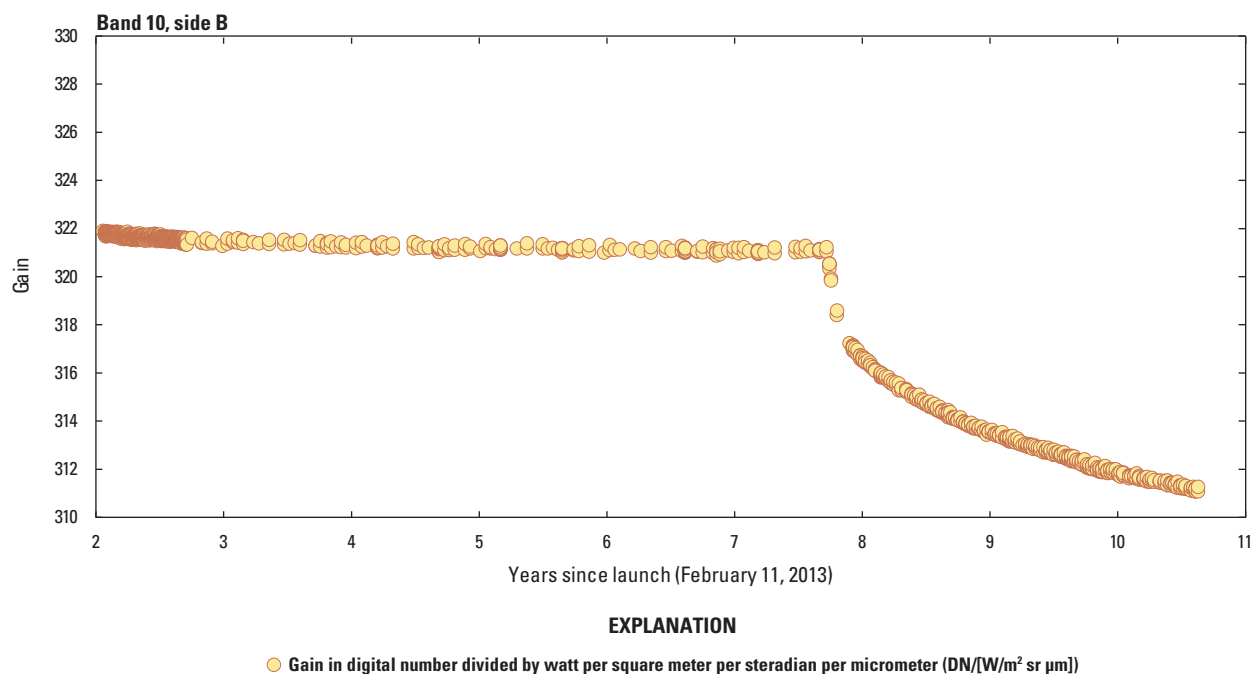


Figure 63. Landsat 8 Thermal Infrared Sensor band 10 radiometric stability (side B).

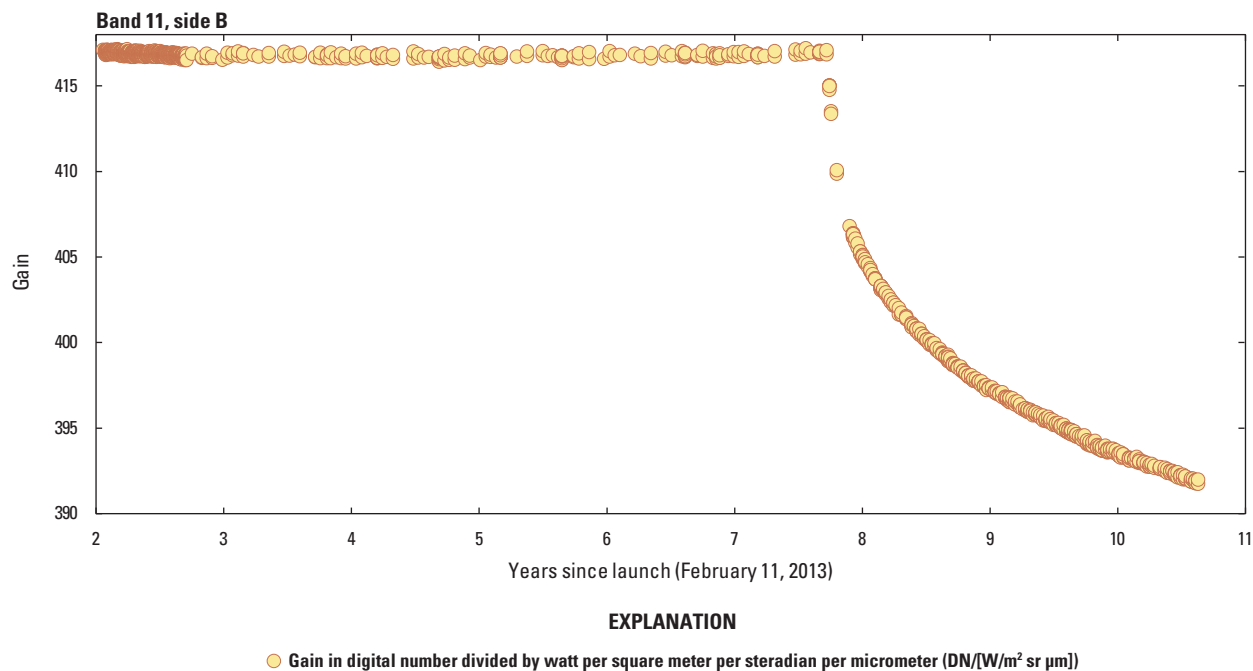


Figure 64. Landsat 8 Thermal Infrared Sensor band 11 radiometric stability (side B).

time (USGS, 2021d). Updates can be made to the calibration parameters used in processing the data to L1 when a substantial change is detected in the calibrator trends.

The lifetime effect of Landsat 8 OLI gain updates is shown in [figure 65](#). A slow decay in CA and blue band calibration response was observed ([figs. 52 and 53](#), respectively). The absolute radiometric calibration for the CA band has been actively modeled since April 2015, and an update to the calibration parameters was implemented for the blue band in April 2017. In April 2018, it was determined that the response to the working stimulation lamp was diverging from the other calibrators, and the working stimulation lamp was removed from the model that generates the gain updates. Similarly, in October 2019, the working diffuser was removed from the gain model because of diverging trends. In both cases, the new estimates of the radiometric gain were only applied to newly acquired data. When the archive was reprocessed for Collection 2, the updated gains were applied to all data, which changed the calibrated response in the CA and blue bands by as much as 0.15 percent compared to the Collection 1 products. The safehold events in November 2020 caused small changes to the Landsat 8 OLI response, as reflected in [figure 26](#) by the small, systematic error adjustments that were made to the gain models. In July 2021, the CPF was updated to account for as much as a 0.12-percent step change in OLI responsivity caused by the November 2020 safehold events.

The effect of change in average gain for Landsat 8 TIRS bands 10 and 11 since the safehold event on November 1, 2020, is shown in [figure 66](#). The orange line is a modeled gain trend for band 10 based on the Internal Calibrator data ([fig. 63](#)), and the blue line is the gain trend sampled into calibration parameters that ensure there is no more than a 0.5-percent band-average radiometric gain change over the CPF period in the L1 products. Likewise, for band 11, the magenta line is a modeled gain trend based on the Internal Calibrator data ([fig. 64](#)), and the yellow line is the gain trend sampled into calibration parameters. Because of the relatively sharp decrease in response shortly after the safehold

events, when compared with the response before the safehold events, calibration parameters were issued more frequently to ensure high quality L1 products. As the rate of degradation has slowed, updated calibration parameters have returned to quarterly issuance.

Landsat 8 Relative Gains

Relative gains account for the differences in responsivity between detectors within a spectral band. OLI relative gains are monitored using solar diffuser acquisitions, side slither acquisitions (which entail a 90-degree yaw maneuver over an invariant site to flatten the data), and scene statistics. Quarterly updates are completed using data from the solar diffuser acquisitions from quarter 2 (April–June), 2023. Starting with the release of Collection 2, TIRS relative gain calibration updates also were completed quarterly using blackbody collects from the previous quarter. These calibration updates removed detector-to-detector striping (USGS, 2021d).

Typical per-detector changes in relative gains between the previous quarter and this quarter for several bands are shown in [figures 67, 68, 69, and 70](#) by analyzing data from within each quarter. In each figure, the x-axis indicates the detector number, and the y-axis indicates the change in relative gain between the quarters as a ratio. These changes in responsivity are accounted for in the L1 product by updating the following quarter's CPF.

The OLI detectors that have indicated a sudden change in responsivity of 0.5 percent or greater in the SWIR 1 and SWIR 2 bands since launch are shown in [figures 71 and 72](#). The x-axis indicates the date of the jump in responsivity, and the y-axis signifies the detector number. The observed responsivity jumps seem to be randomly scattered in time and location on the focal plane so do not seem to be associated with an instrument event or failure. These jumps are only seen in the SWIR bands (SWIR 1, SWIR 2, and cirrus); the visible and near infrared band detectors have not indicated any jump behavior over the whole mission.

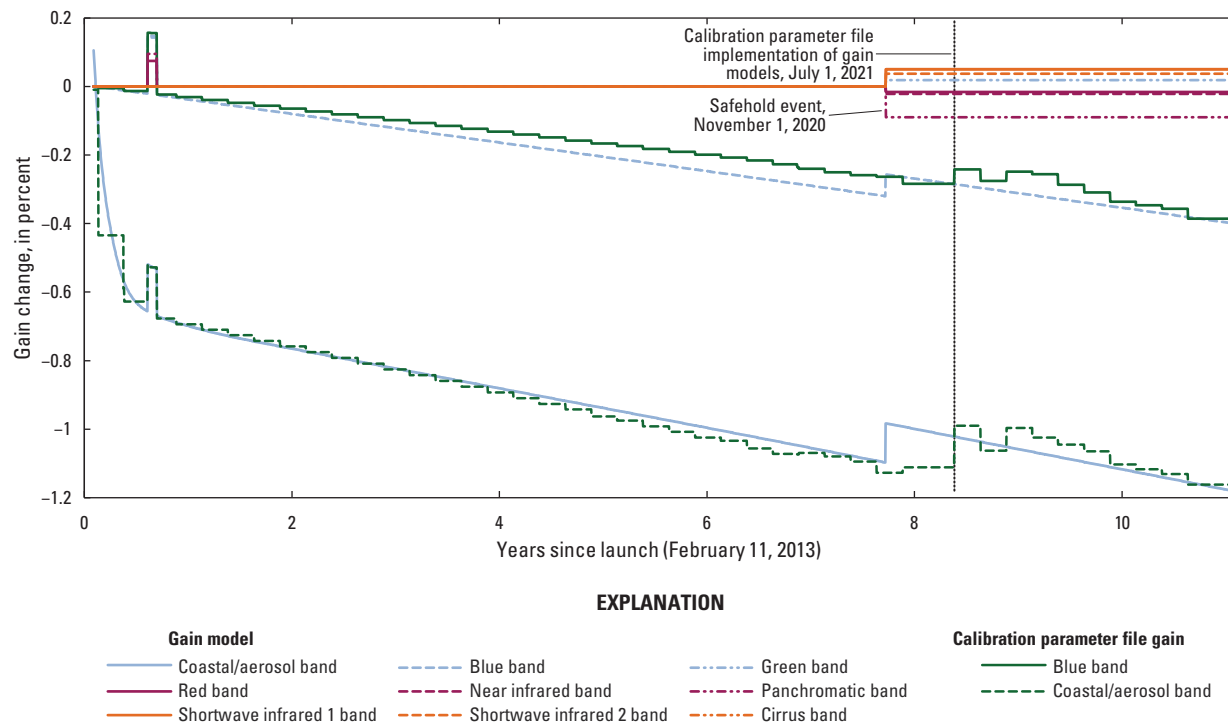


Figure 65. Landsat 8 Operational Land Imager lifetime gain trends and calibration gain updates.

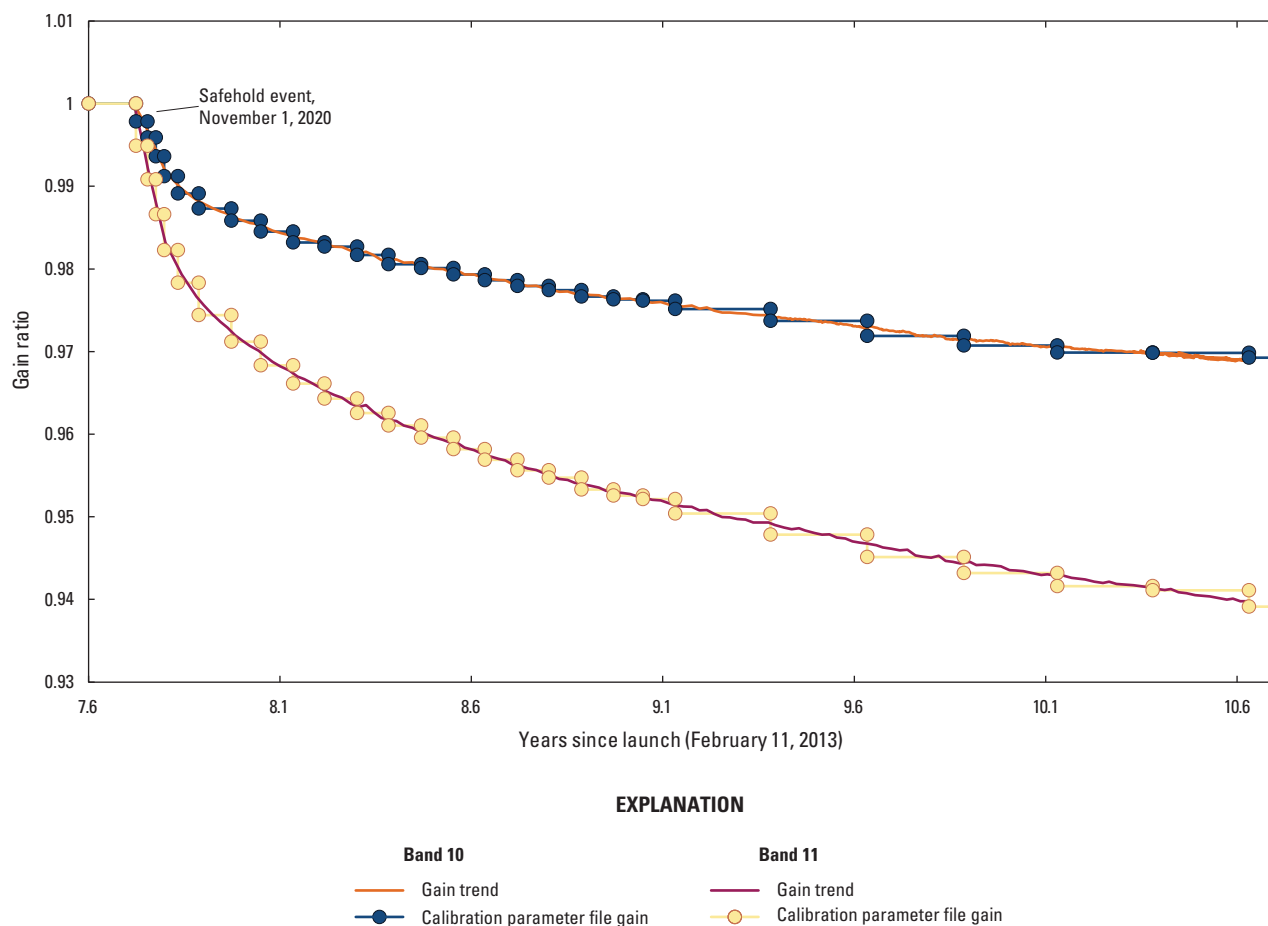


Figure 66. Landsat 8 Thermal Infrared Sensor gain degradation since the safehold event on November 1, 2020.

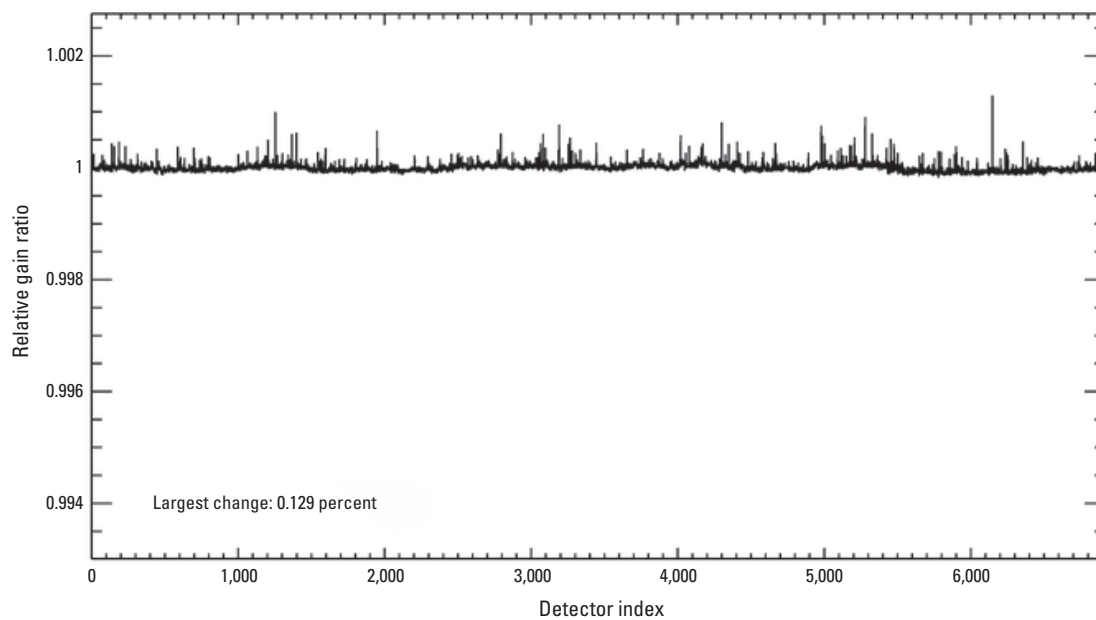


Figure 67. Landsat 8 Operational Land Imager coastal/aerosol band per-detector change in relative gains between quarter 2 and quarter 3, 2023.

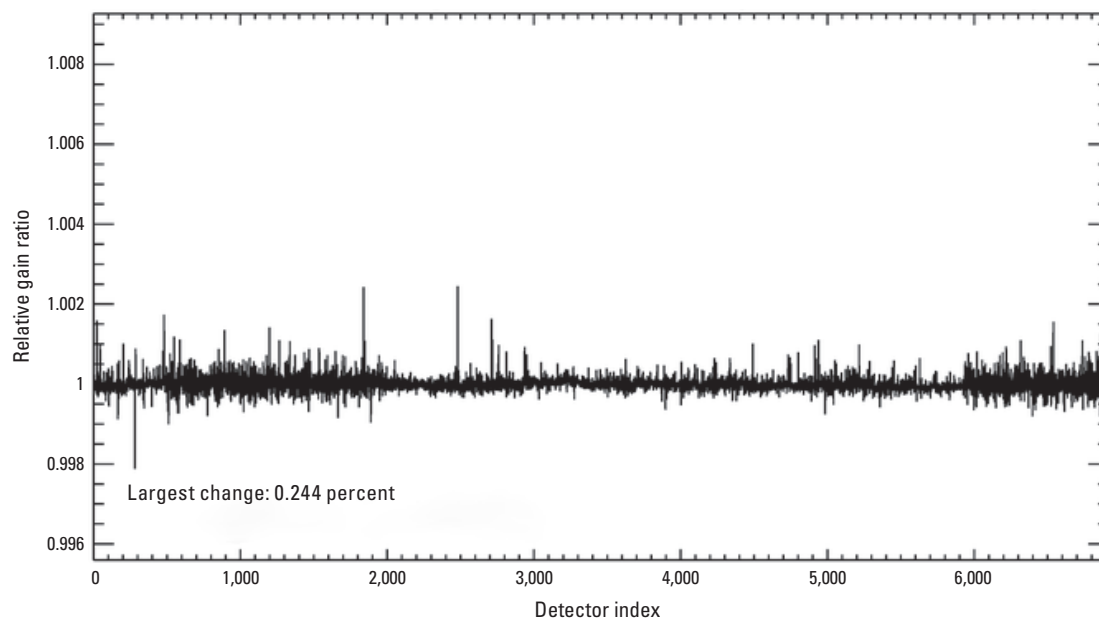


Figure 68. Landsat 8 Operational Land Imager shortwave infrared 1 band per-detector change in relative gains between quarter 2 and quarter 3, 2023.

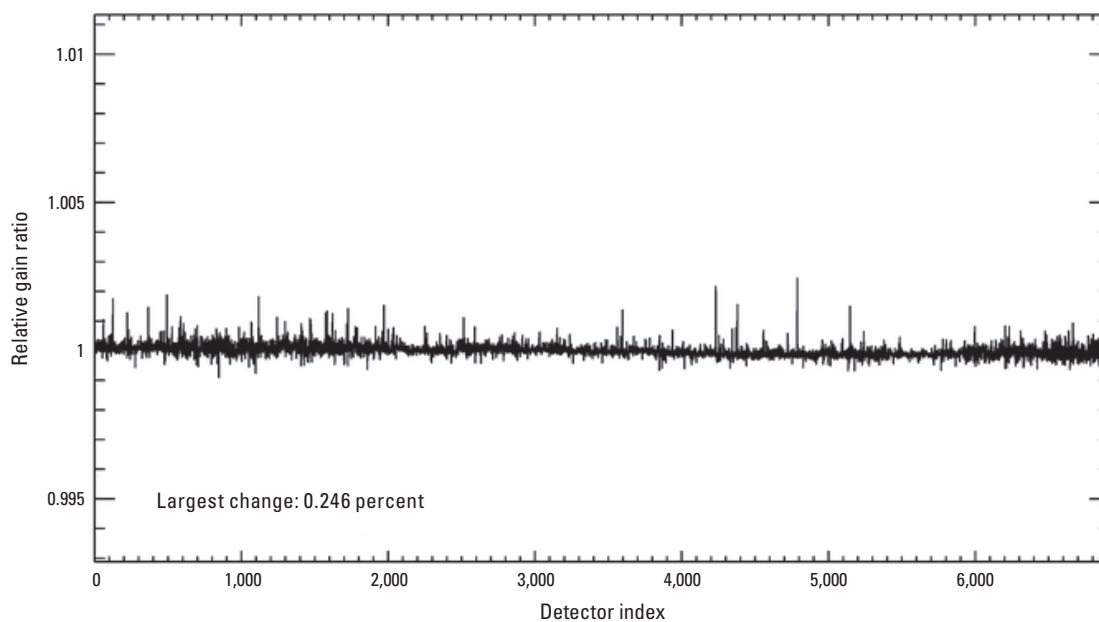


Figure 69. Landsat 8 Operational Land Imager shortwave infrared 2 band per-detector change in relative gains between quarter 2 and quarter 3, 2023.

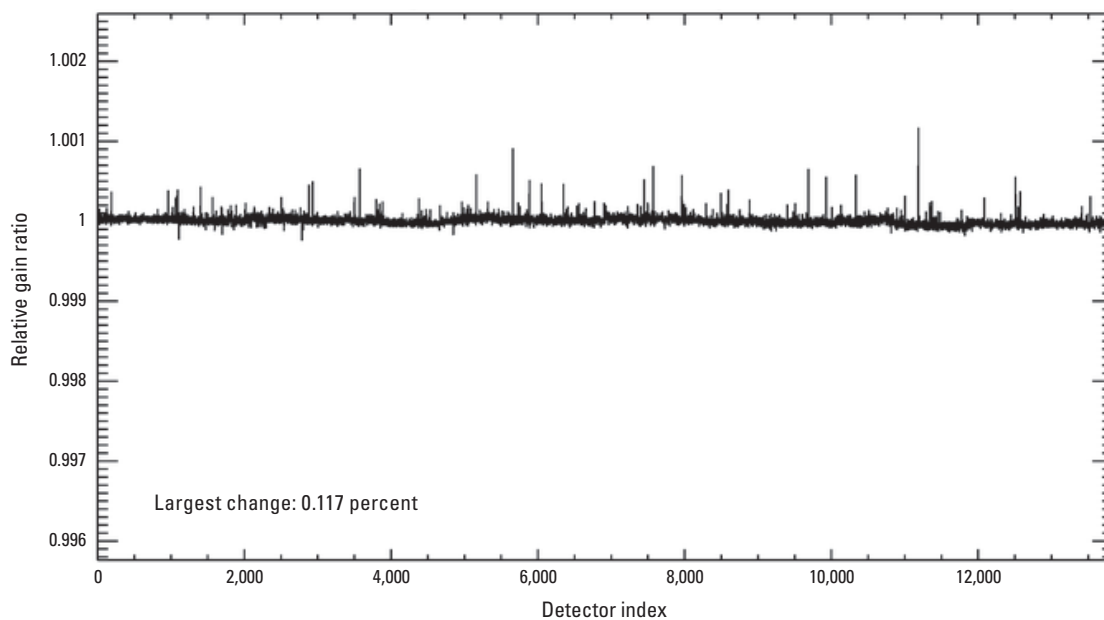


Figure 70. Landsat 8 Operational Land Imager panchromatic band per-detector change in relative gains between quarter 2 and quarter 3, 2023.

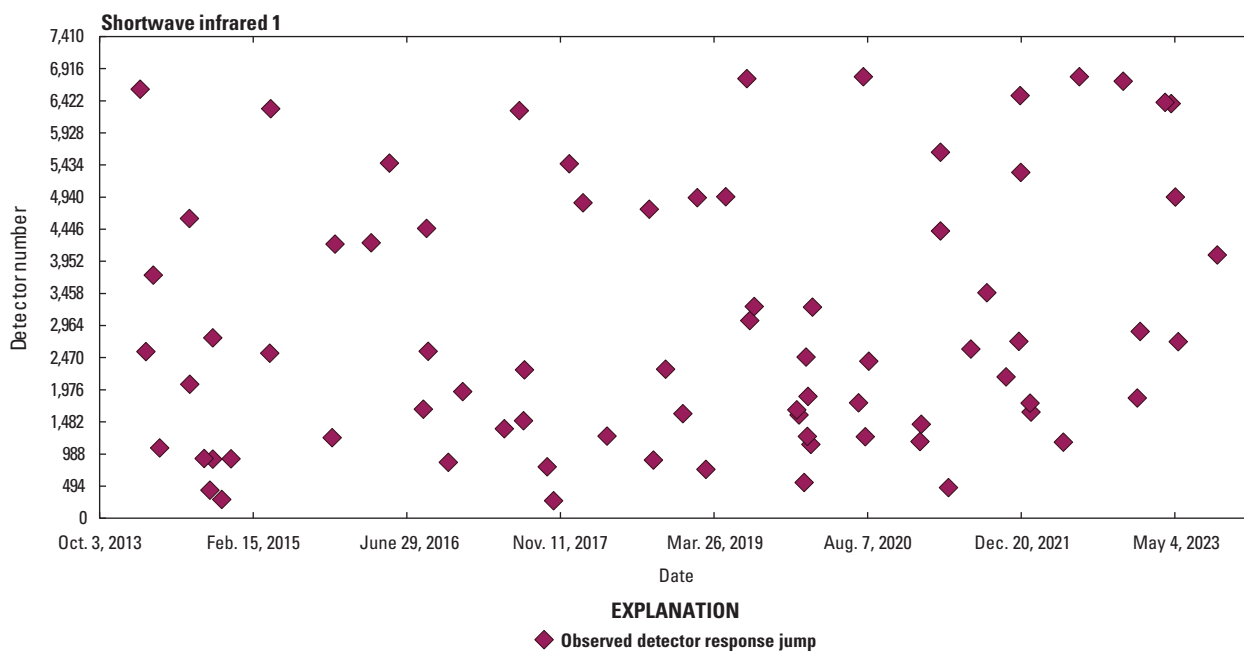


Figure 71. Landsat 8 Operational Land Imager shortwave infrared 1 lifetime jumps in detector responsivity.

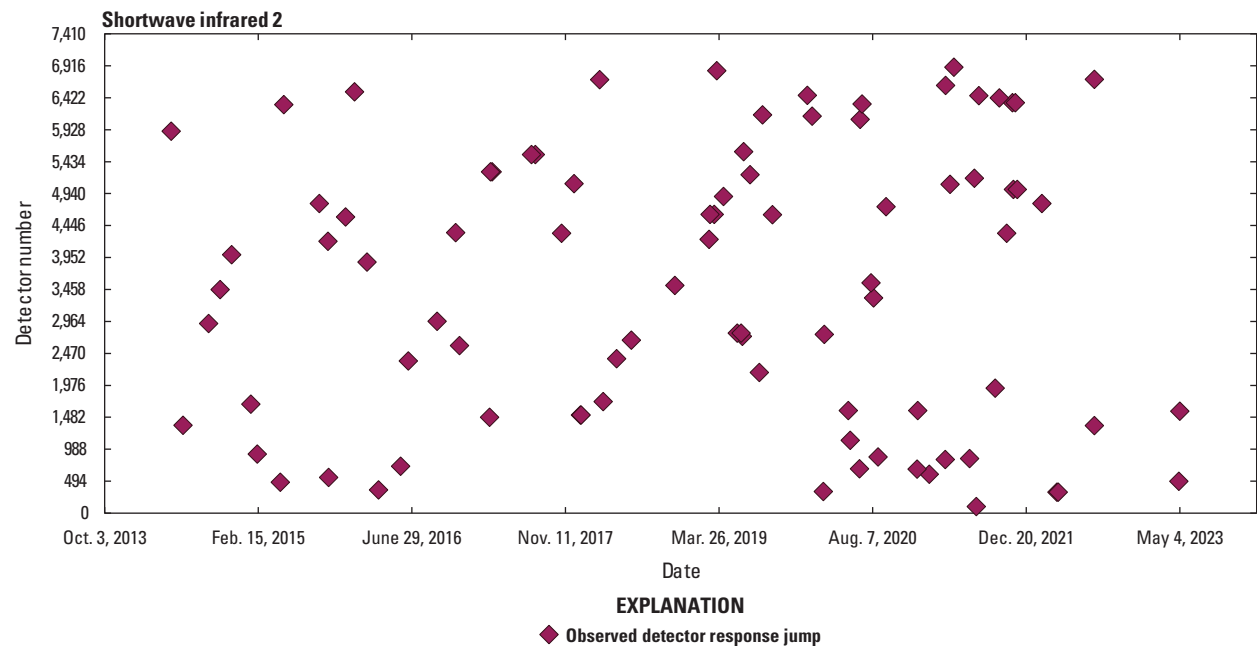


Figure 72. Landsat 8 Operational Land Imager shortwave infrared 2 lifetime jumps in detector responsivity.

Landsat 8 Geometric Performance Summary

The Landsat 8 on-orbit geometric performance for the reporting quarter (quarter 3, July–September 2023) meets all requirements as outlined in USGS (2019b). The quarterly results summary is provided in [table 7](#).

Landsat 8 Band Registration Accuracy

Internal band registration measures how accurately the various Landsat 8 spectral bands are geometrically aligned to each other. The assessment provides a numerical evaluation of the accuracy of the band registration within an image using automated cross-correlation techniques between the bands to be assessed (USGS, 2021d).

Landsat 8 OLI band registration performance has been stable over time. Quarterly band-to-band maximum registration accuracy for each band combination except for the

Table 7. Landsat 8 geometric performance summary, quarter 3 (July–September), 2023.

[The previous quarter is quarter 2 (April–June), 2023. OLI, Operational Land Imager; <, less than; LE90, linear error with 90-percent confidence; CE90, circular error with 90-percent confidence; L1T, Level 1 terrain-corrected product; >, greater than; TIRS, Thermal Infrared Sensor]

Requirement	Measured value from this quarter	Measured value from previous quarter ¹	Required value	Unit
OLI band registration accuracy (all bands)	4.47	4.40	<4.5	Meter (LE90)
OLI band registration accuracy (no cirrus)	3.40	3.30	<4.5	Meter (LE90)
Absolute geodetic accuracy	13.6	23.1	<65	Meter (CE90)
Relative geodetic accuracy	7.6	7.5	<25	Meter (CE90)
Geometric (L1T) accuracy	8.4	11.5	<12	Meter (CE90)
OLI edge slope	0.030	0.030	>0.027	1 per meter
TIRS band registration accuracy	8.6	8.7	<18	Meter (LE90)
TIRS-to-OLI registration accuracy	17.6	18.1	<30	Meter (LE90)

¹From Haque and others (2023b).

cirrus band is shown in [figure 73](#). Within the figure, blue bars indicate maximum registration accuracy in the line direction, and green bars indicate maximum registration accuracy in the sample direction. Lifetime OLI band registration accuracy for all bands is 4.2 meters (not shown), and lifetime OLI band registration accuracy for all bands, excluding cirrus, is 3.3 meters, which is well within the instrument specification accuracy. OLI band registration accuracy for all bands during quarter 3, 2023, is 4.5 meters (not shown), and OLI band registration accuracy for all bands, excluding cirrus, during quarter 3, 2023, is 3.4 meters.

Landsat 8 TIRS band registration performance has been stable throughout the instrument's lifetime, including after changes in Scene Select Mechanism (SSM) operation beginning in December 2014. Behavior is well within specification, as shown in [figure 74](#), and quarter 3, 2023, results are consistent with past performance. Within the figure, blue bars indicate maximum registration accuracy in the line direction, and green bars indicate maximum registration accuracy in the sample direction. Lifetime TIRS band registration accuracy is 9.0 meters, and during quarter 3, 2023, the accuracy is 8.6 meters. Since quarter 3 (July–September), 2020 (Collection 2 data), registration bias between the line and sample directions has reduced, which may be because of better SSM pointing stability, the TIRS relative gain update, or both.

Lifetime Landsat 8 TIRS to OLI band registration accuracy by quarter is shown in [figure 75](#). Before the Collection 2 CPF update, seasonal effects are noticeable but leveled off after the release of Collection 2 in December 2020, as indicated by the closely aligned line (blue bars) and sample (green bars) accuracies. From Haque and others (2023a), alignment

offset was greater for quarter 2 and quarter 3, 2022, because of changes in the alignment trends between the two instruments. Lifetime Landsat 8 TIRS to OLI registration accuracy (excluding the cirrus band) is 19.6 meters in the line direction and 18.0 meters in the sample direction. Quarter 3, 2023, TIRS to OLI registration accuracy (excluding the cirrus band) is 17.6 meters in the line direction and 16.7 meters in the sample direction.

Landsat 8 Operational Land Imager to Thermal Infrared Sensor Alignment

Landsat 8 OLI to TIRS alignment knowledge is critical to ensure that the L1 product accuracy requirements can be met. The alignment between OLI and TIRS instruments is periodically measured using correlation-based methods to ensure that the band-to-band alignment requirements for all Landsat 8 bands can be met (USGS, 2021d). The alignment estimates are used to update the calibration parameters in the CPFs when the observed changes are determined to affect the performance requirements.

Landsat 8 TIRS to OLI pitch alignment measurements over instrument lifetimes are shown in [figure 76](#). The November 2020 safehold events did substantially affect pitch alignment, but the ECCOE Landsat Cal/Val Team continues to monitor pitch alignment. From Haque and others (2022), in quarter 4, 2021, a small change in the TIRS to OLI pitch alignment was observed, which is similar to the seasonal trend observed in previous years; however, the magnitude of this trend was not the same as before, so it was unclear whether

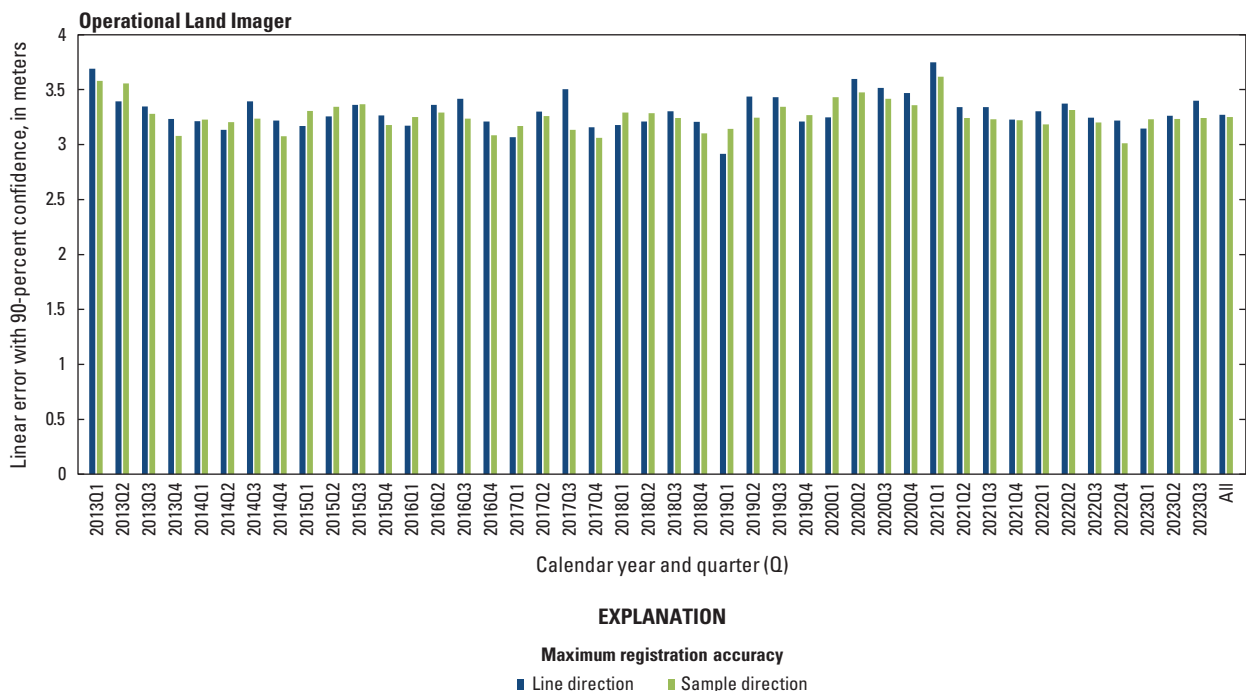


Figure 73. Landsat 8 Operational Land Imager lifetime band (excluding cirrus) registration accuracy by quarter.

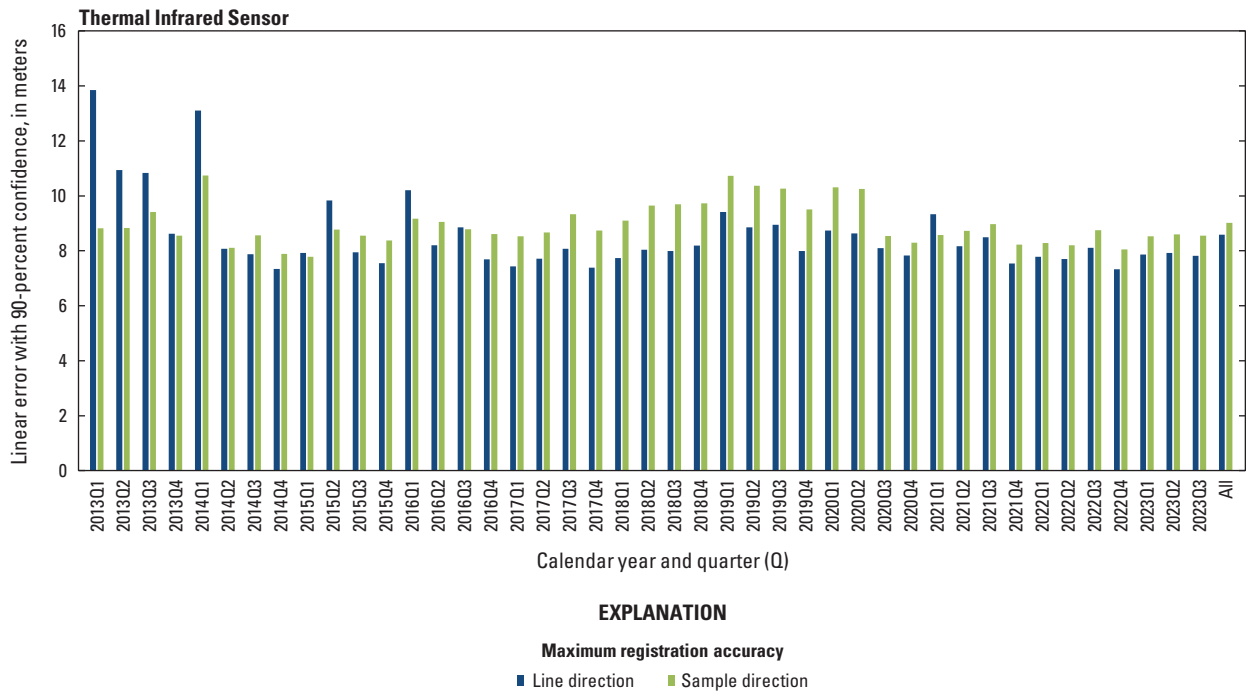


Figure 74. Landsat 8 Thermal Infrared Sensor lifetime band registration accuracy by quarter.

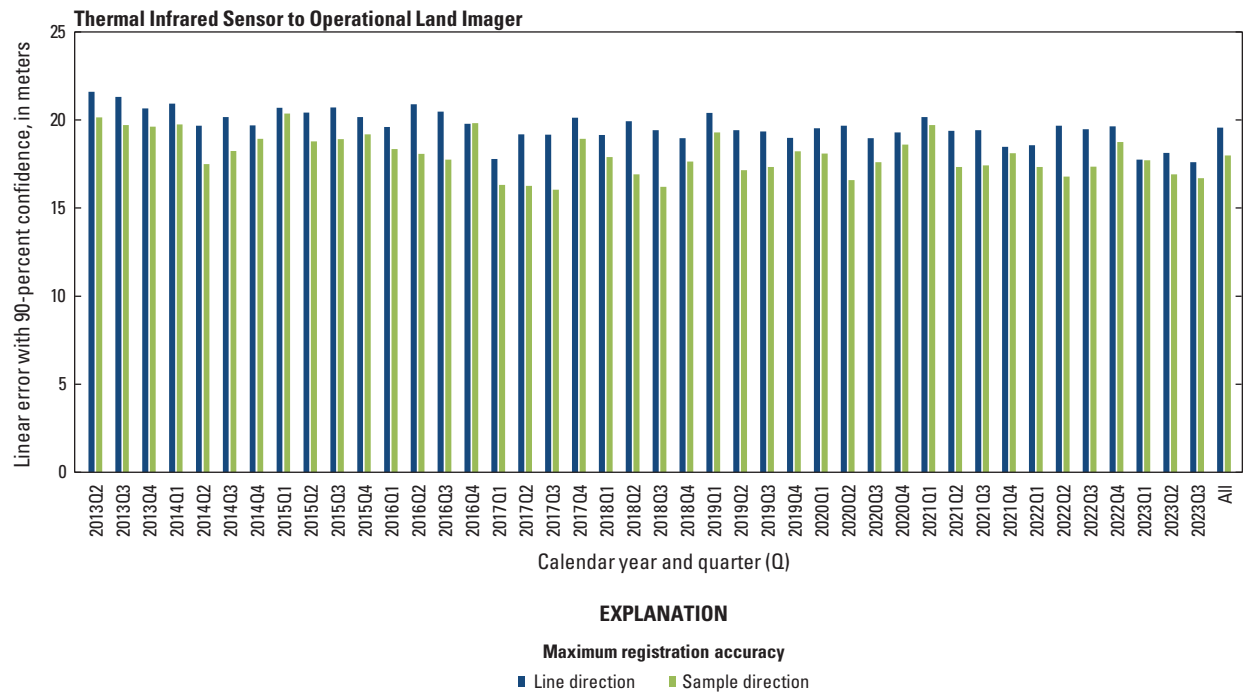


Figure 75. Landsat 8 Thermal Infrared Sensor to Operational Land Imager lifetime band (excluding cirrus) registration accuracy by quarter.

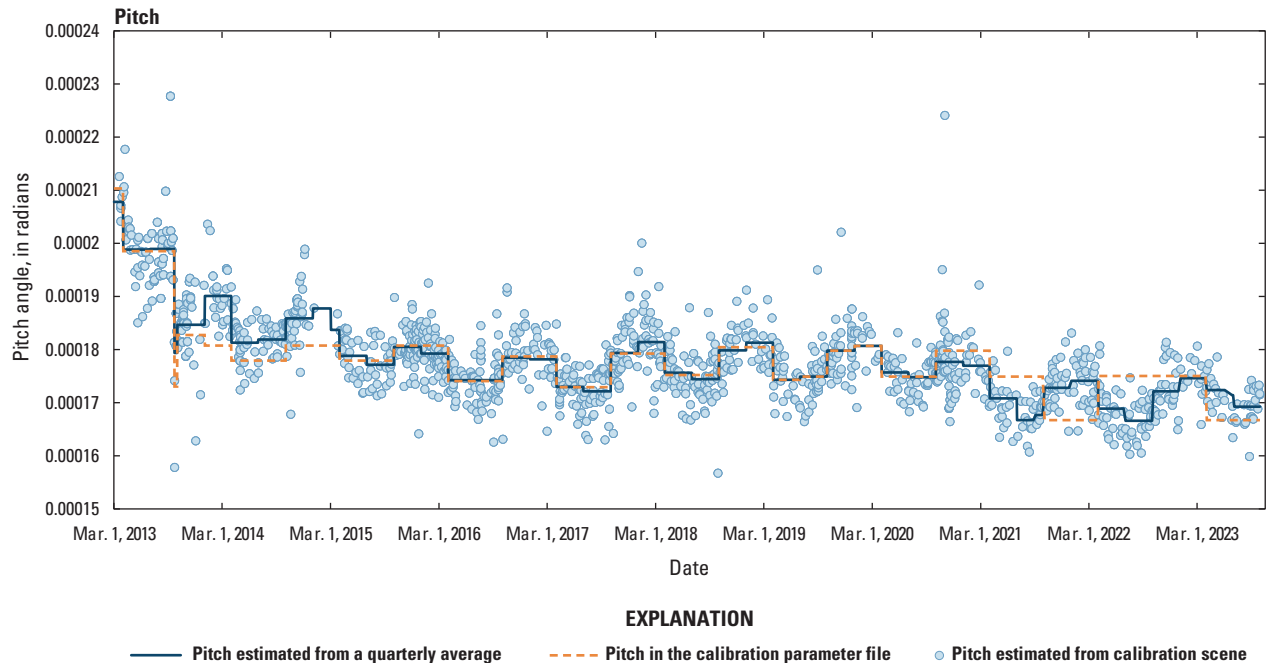


Figure 76. Landsat 8 Thermal Infrared Sensor to Operational Land Imager lifetime pitch alignment.

this new trend would continue or not. The trend continued in quarter 1, so a CPF update was issued in quarter 2, 2022, for residual corrections to the alignment parameters. At this point of time, predictive estimates based on previous quarters, not knowing if the seasonal trend will be observed or not, made the CPF inconsistent with the seasonal pattern. With an intention to align the CPF more with the seasonal pattern for better prediction, subsequent predictive CPF updates for quarter 3, 2022; quarter 4, 2022; and quarter 1, 2023, were not changed. Based on previously observed seasonal patterns in the alignment trend, a TIRS-OLI alignment update was made for quarter 2, 2023, and unchanged for quarter 3, 2023. The April 2023 TIRS SSM excursion anomaly did not indicate any substantial effects in the TIRS to OLI pitch alignment. The lifetime TIRS to OLI roll alignment is shown in [figure 77](#), and the lifetime TIRS to OLI yaw alignment is shown in [figure 78](#). The April 2023 TIRS SSM excursion anomaly did not indicate any substantial effects to roll or yaw alignment. Each light blue symbol on these figures represents one calibration scene, the dark blue solid lines indicate quarterly alignment averages, and the orange dashed lines indicate applied Collection 2 CPF correction values.

Landsat 8 Geometric Accuracy

The Landsat 8 geometric assessment evaluates the absolute positional accuracy of the image products with respect to a ground (geometric) reference. The geometric accuracy assessment estimates the geometric error between the L1TP products and GCPs using automated cross-correlation techniques (USGS, 2021d).

Based on analysis results, relative accuracy of the Collection 2 GCPs is comparable to the DOQ supersites, which are sites created from a mosaic of highly accurate high-resolution terrain-corrected aerial data. Comparatively, relative accuracy of the Collection 2 GCPs is substantially better than the internal consistency of the Collection 1 GCPs. Overall, cloud contaminated scene-based results are the primary contributor to poor geometric accuracy from L1TP products. Lifetime quarterly Landsat 8 geometric accuracy at a CE90 is shown in [figure 79](#). Blue bars indicate the geometric accuracy estimated over supersite paths/rows (calibration sites) with cloud-free scenes (using DOQ GCPs for the trend since quarter 1 [January–March], 2022), yellow bars indicate geometric accuracy estimated over supersite paths/rows (calibration site scenes subsetting from all the L1TP scenes with no cloud constraints) using Collection 2 GCPs, and green bars indicate geometric accuracy estimated over all L1TP scenes processed in Collection 2 using Collection 2 GCPs (no cloud constraints). All results for this quarter are within the accuracy specification.

Lifetime and quarter 3, 2023, geometric accuracies for L1TP products are 3.7 and 3.6 meters when compared against cloud-free scenes over supersite paths/rows, 5.3 and 5.0 meters when compared against all L1TP scenes over supersite paths/rows only, and 10.3 and 8.4 meters when analyzing all the L1TP scenes processed in Collection 2, respectively. Note that seasonal effect is a factor in accuracy results.

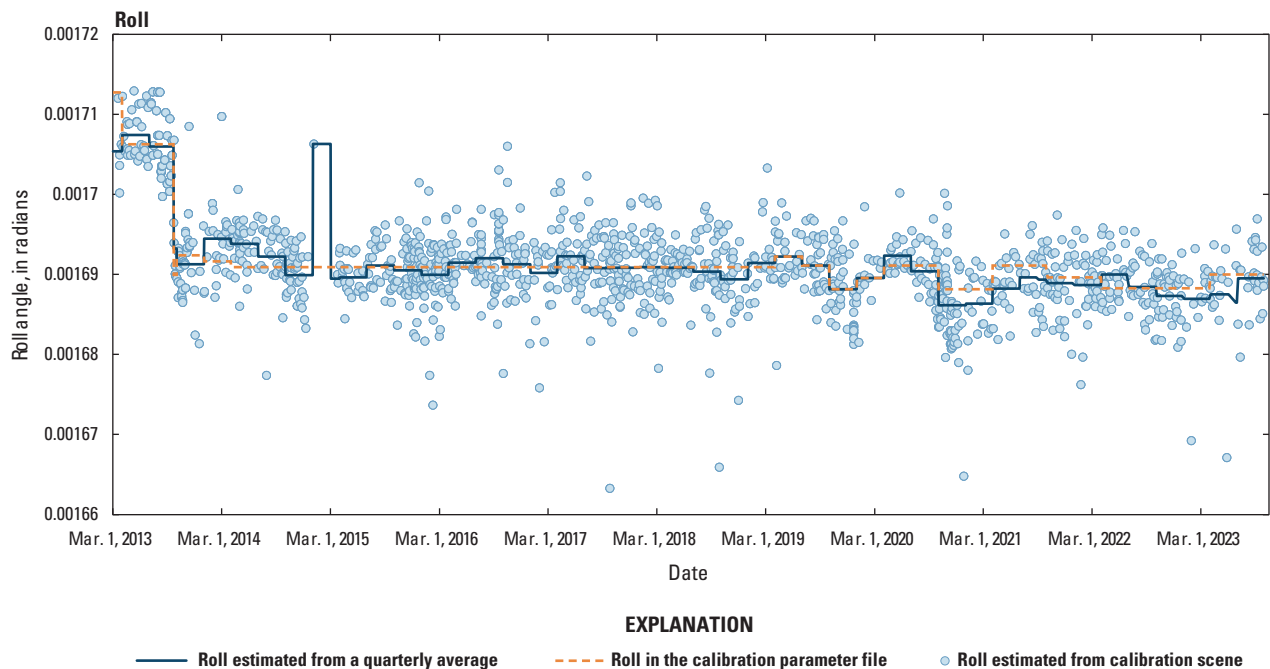


Figure 77. Landsat 8 Thermal Infrared Sensor to Operational Land Imager lifetime roll alignment.

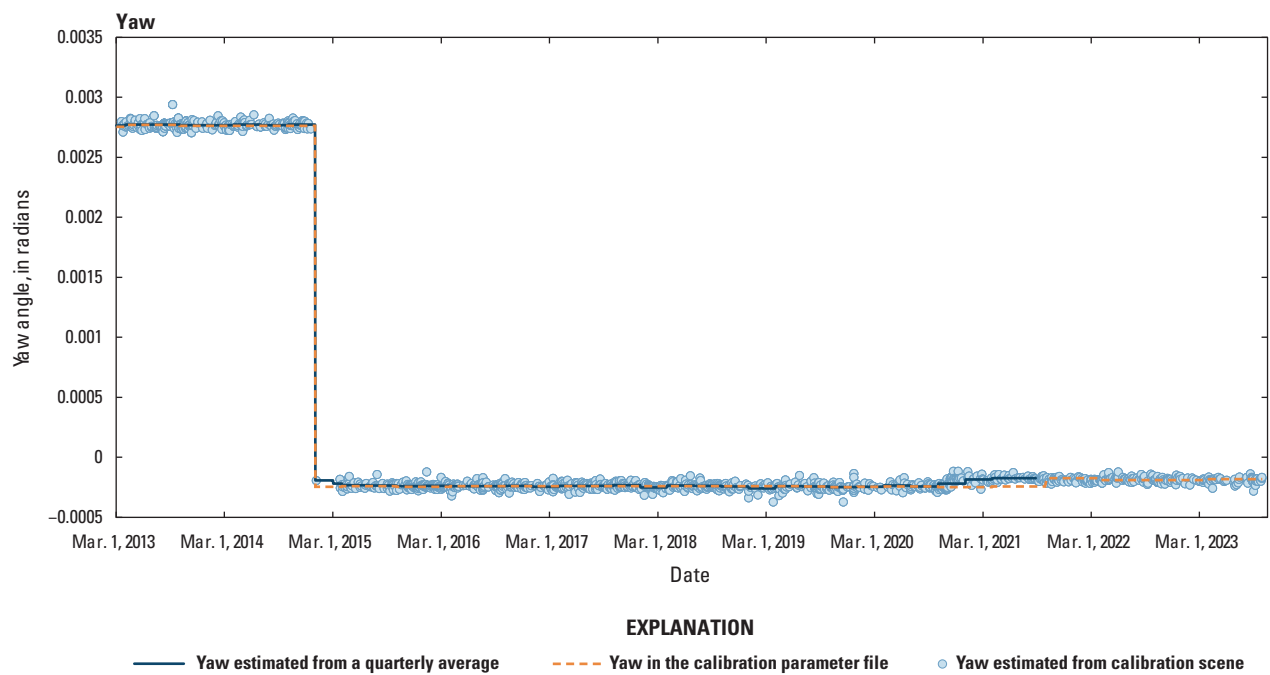


Figure 78. Landsat 8 Thermal Infrared Sensor to Operational Land Imager lifetime yaw alignment.

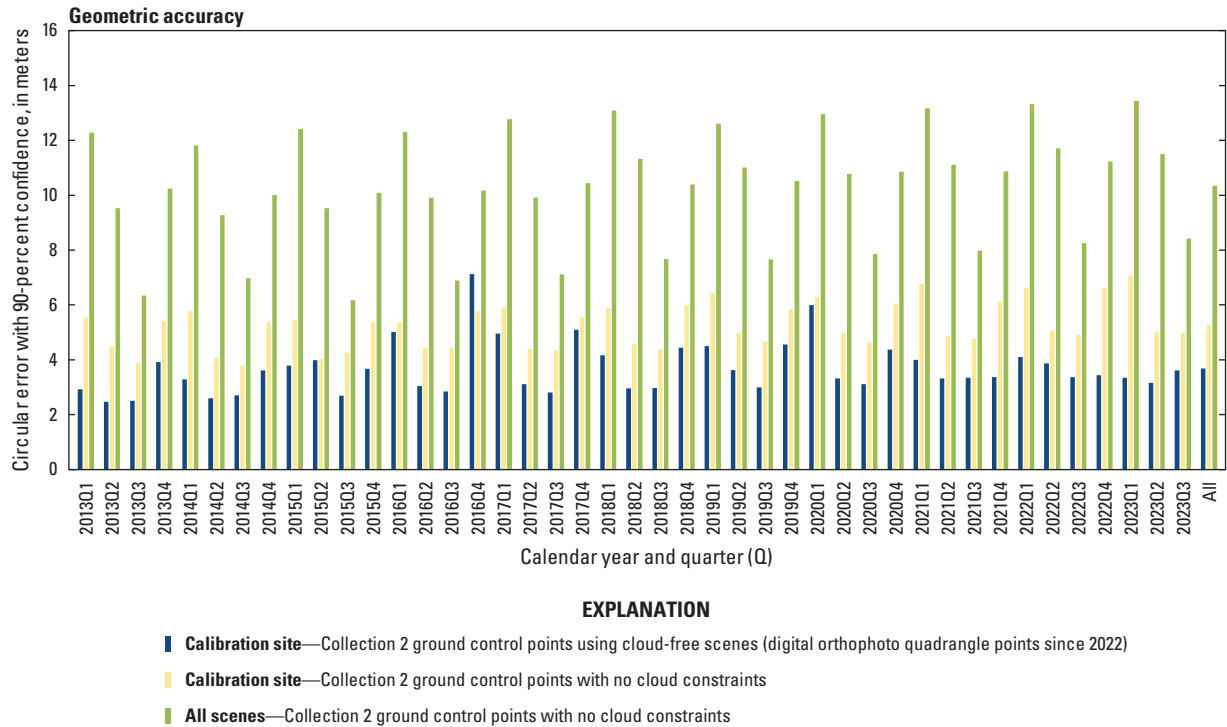


Figure 79. Landsat 8 lifetime geometric accuracy by quarter.

Landsat 8 Geodetic Accuracy

The purpose of the geodetic accuracy assessment is to ensure that the Landsat 8 L0Rp data can be successfully processed into L1 systematic products that meet the system requirement of 65 meters at a CE90 horizontal accuracy. To measure the accuracy, calibration scenes are automatically correlated with data from the panchromatic band to measure the discrepancy between the known ground location and the position predicted by the OLI geometric model (USGS, 2021d).

Based on analysis results, absolute accuracy of the Collection 2 GCPs is comparable to the DOQ supersites and is substantially better compared to the Collection 1 GCPs (Rengarajan and others, 2020). Lifetime quarterly Landsat 8 geodetic accuracy (CE90) is shown in [figure 80](#). Blue bars indicate the accuracy estimated using DOQ supersite paths/

rows (calibration site), and green bars indicate accuracy estimated from all L1TP scenes processed in Collection 2 using Collection 2 GCPs. As in the case with the geometric accuracy, a wide variety of scene types (cloud contaminated, islands, desert, snow covered, ice sheets, and so on) are the primary contributor to the poor geodetic accuracy for Collection 2 GCP-based results.

Although quarters 1, 2, and 3, 2021, indicated a slight increase in the geodetic accuracy offset, the lifetime results have been consistently well within the accuracy specification. The increase in the geodetic accuracy is because of a systematic bias in the along-track direction observed since the November 2020 safehold events. After the bias stabilized, an update to the sensor alignment parameters in the CPF was released in quarter 4, 2021, resulting in a decrease in the observed geodetic offsets. An additional sensor alignment

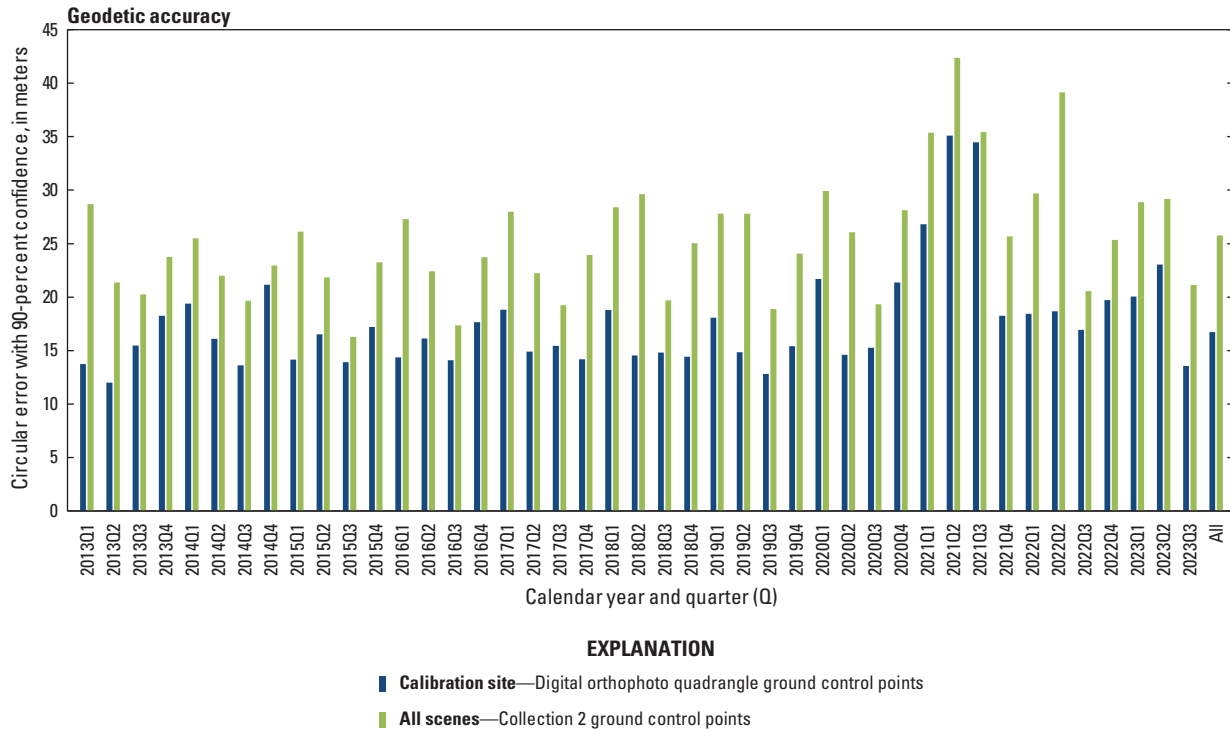


Figure 80. Landsat 8 lifetime geodetic accuracy by quarter.

update was released in quarter 2, 2022, in response to an along-track offset that was greater than 10 meters and continuing to increase. Geodetic accuracy has been within 10 meters (considering both along-track and across-track directions) since then, including after the April 2023 TIRS SSM excursion anomaly, and no sensor alignment update was necessary. Lifetime geodetic accuracies for systematic products are 16.7 meters when compared using DOQ GCPs over supersites and 25.8 meters when compared using Collection 2 GCPs over all the scenes processed in Collection 2, respectively.

Landsat 7 Radiometric Performance Summary

The Landsat 7 on-orbit radiometric performance for this reporting quarter (quarter 3, July–September 2023) was fully characterized and the details are summarized in this section.

Landsat 7 Onboard Calibrator Trends

The ETM+ has three onboard calibration devices: the Internal Calibrator, the Partial Aperture Solar Calibrator, and the Full Aperture Solar Calibrator. These calibration devices have been used to monitor radiometric stability since launch (April 15, 1999; Markham and others, 1994; Barsi and others, 2016; USGS, 2019a).

The responsivity of the ETM+ as determined from the onboard calibrators is shown in [figure 81](#) for the blue band and [figure 82](#) for the SWIR 1 band. The three calibrators all indicate degradation over time, although at varying rates that changed at different times. The degradation shown here is thought to be primarily within the calibrators and not because of the ETM+ detectors or electronics (Markham and others, 2012). Furthermore, preliminary analyses indicate no substantial change in response after a series of orbit-lowering maneuvers, beginning on April 6, 2022. Additional information about the Landsat 7 orbit lowering is available at <https://www.usgs.gov/centers/eros/news/landsat-7-lowered-standard-landsat-orbit>.

Landsat 7 Coherent Noise

Coherent noise in the ETM+ has been monitored since launch using a fast Fourier transform on dark nighttime data (Barsi and others, 2016). The Landsat 7 lifetime coherent noise results for specific band and detector combinations at designated frequencies are shown in [figure 83](#). Magnitudes of most coherent noise components remain low, but a positive trend in coherent noise power of SWIR 1 (band 5) detector 12 (orange circles) has been observed. In this SWIR 1 detector 12 case, noise power decreases with instrument on time along an interval, so scenes acquired earlier in an interval are subject

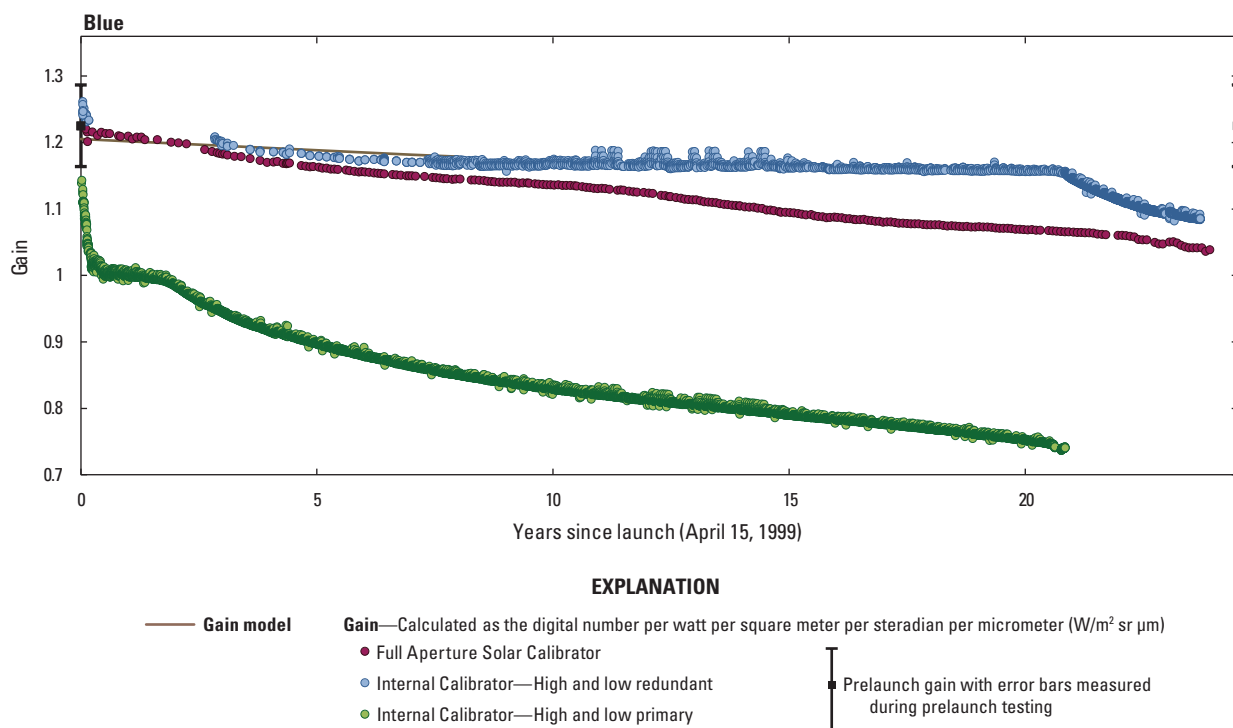


Figure 81. Landsat 7 Enhanced Thematic Mapper Plus blue band lifetime gains.

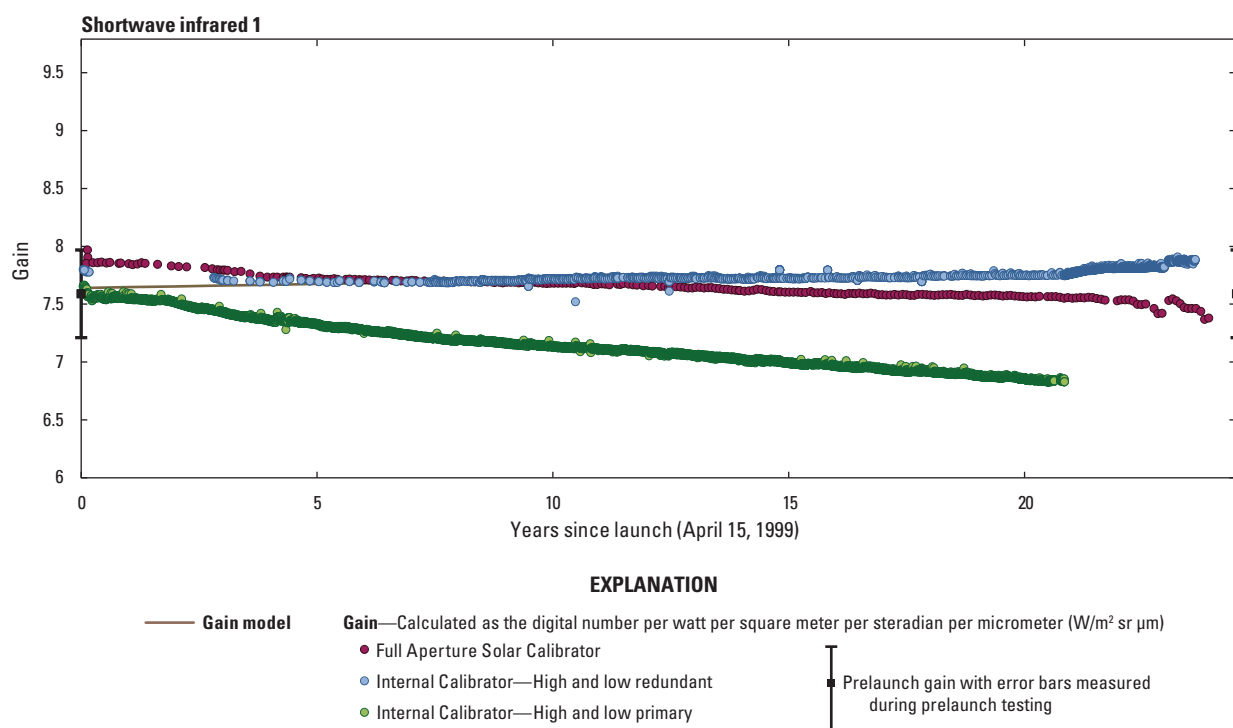


Figure 82. Landsat 7 Enhanced Thematic Mapper Plus shortwave infrared 1 band lifetime gains.

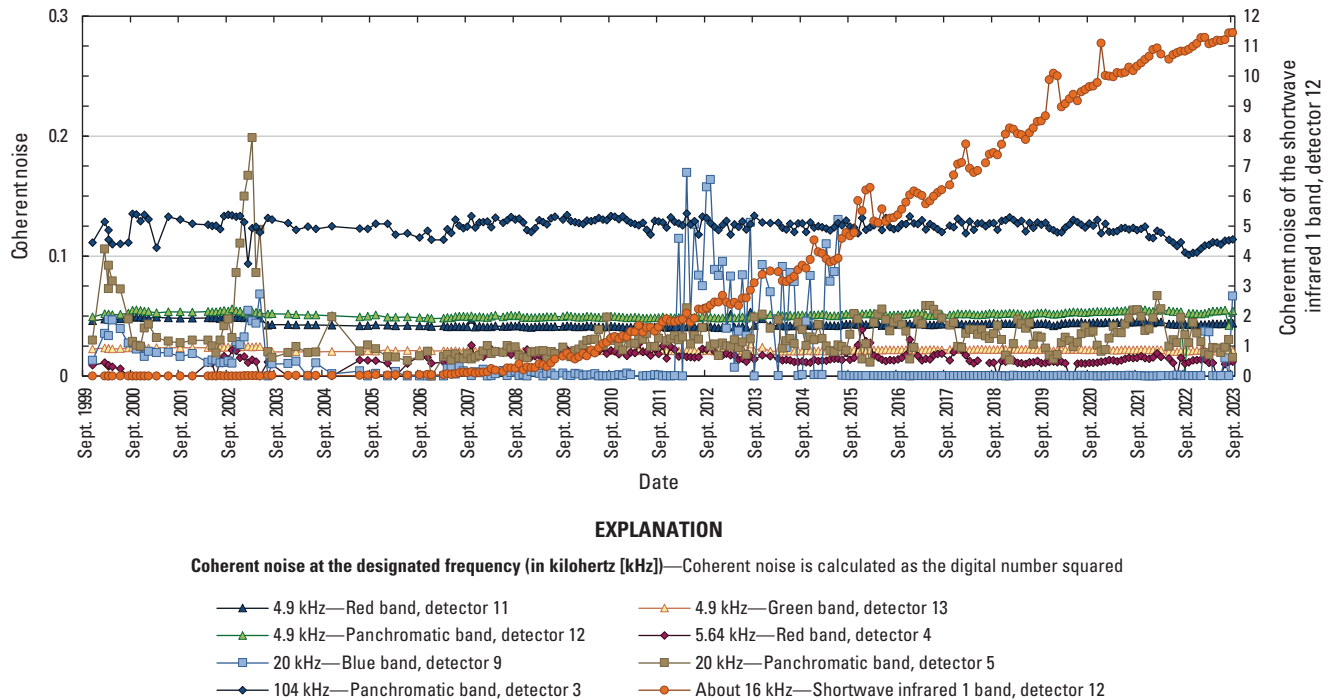


Figure 83. Landsat 7 Enhanced Thematic Mapper Plus lifetime coherent noise.

to stronger coherent noise features. In 2010, only the first few scenes acquired in an interval were affected by the coherent noise, but by 2015, the noise was strong enough that it was still present as many as 15 minutes later (fig. 83).

Landsat 7 Pseudoinvariant Calibration Sites Trending

PICS also are used to monitor the ETM+ radiometric stability. Several of the PICS regions (Committee on Earth Observation Satellites, 2021) defined by CNES were used to develop a new gain model for ETM+, which was applied starting in 2013 (USGS, 2021c). The Cal/Val Team uses multiple PICS for monitoring radiometric changes because of the temporal stability of those sites (Tuli and others, 2019).

PICS trending calculates basic statistics from geographic ROIs extracted from geometrically corrected Landsat products. The primary purpose for trending is to repeatedly characterize PICS, save results to the database, and thus enable an automatic monitoring of ETM+ temporal stability.

The lifetime top of atmosphere reflectance values observed over the Libya 4 PICS site (lat 28.55° N., long 23.39° E.) using the CNES ROI are shown in figure 84. The lifetime temporal trends show seasonal effects, which are more substantial in the longer wavelength SWIR bands. After the seasonal effect is removed, a slight indication of deviation from current trends is observed; the deviation is in the negative direction for all bands except SWIR 1, which has a slight deviation in the positive direction. Recent trends indicate deviation in the negative direction in all bands except the blue and green bands, possibly as a result of the orbit lowering.

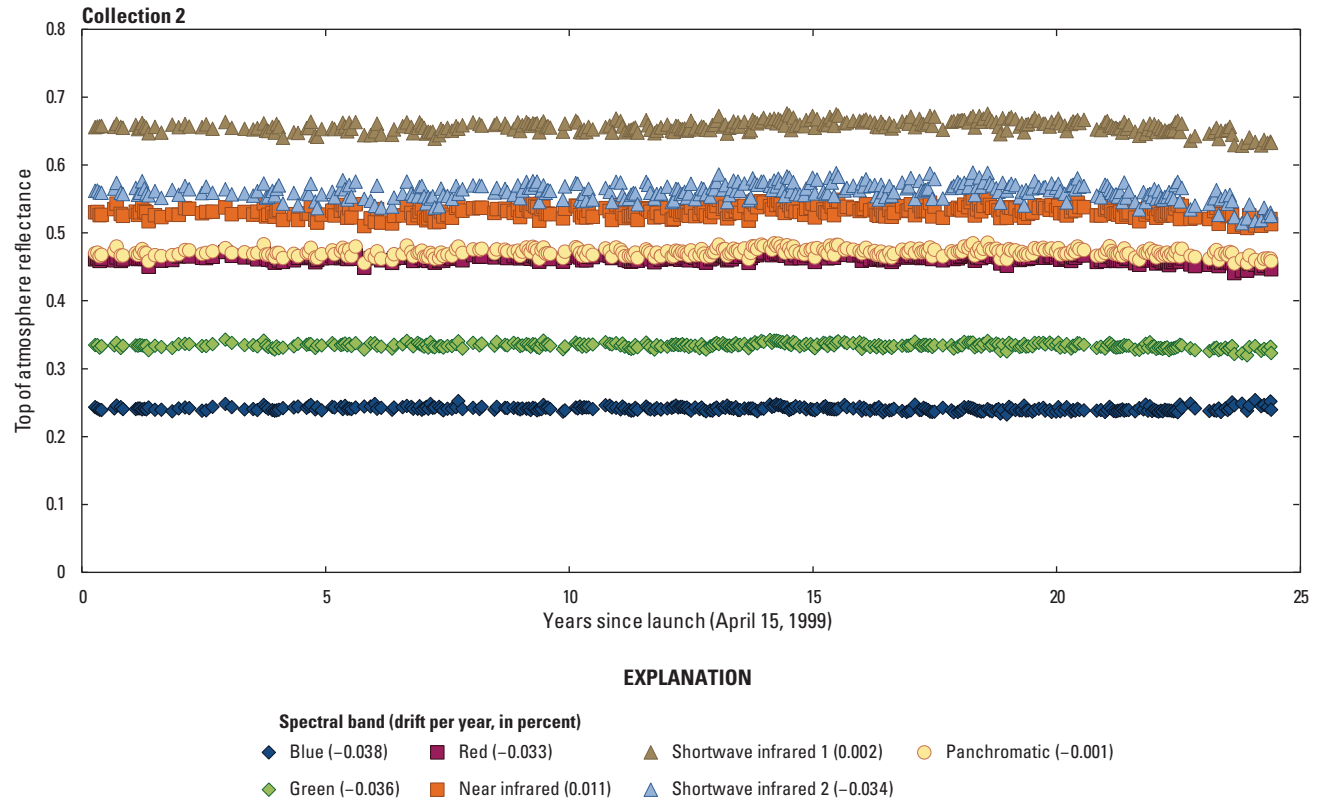


Figure 84. Libya 4 pseudoinvariant calibration site top of atmosphere reflectance trending normalizing/correcting seasonality effects, Collection 2.

Landsat 7 Geometric Performance Summary

The Landsat 7 on-orbit geometric performance for this quarter (quarter 3, July–September 2023) meets all requirements as outlined in USGS (2019a). The quarterly results summary is provided in [table 8](#).

Landsat 7 Geodetic Accuracy

The purpose of the geodetic accuracy assessment is to ensure that the Landsat 7 L0Rp data can be successfully processed into L1 systematic products that meet the system requirement of 250-meter (1σ) accuracy, excluding terrain effects and without the use of GCPs. Geodetic accuracy is monitored using calibration supersites containing GCPs derived from the DOQ aerial photography (U.S. supersites) and Satellite Pour l’Observation de la Terre (SPOT) satellite imagery (Australian supersites).

Table 8. Landsat 7 geometric performance summary, quarter 3 (July–September), 2023.

[The previous quarter is quarter 2 (April–June), 2023. ETM+, Enhanced Thematic Mapper Plus; <, less than; σ , sigma; L1T, Level 1 terrain-corrected product]

Requirement	Measured value from this quarter	Measured value from previous quarter ¹	Required value	Unit
ETM+ band registration accuracy (bands 1–5, 7)	1.8	1.9	<5.1	Meter (1σ)
ETM+ band registration accuracy (thermal [band 6])	5.5	5.8	<10.2	Meter (1σ)
Absolute geodetic accuracy	131.6	124.0	<250	Meter (1σ)
Relative geodetic accuracy	12.2	13.1	<25	Meter (1σ)
Geometric (L1T) accuracy	6.0	6.3	<12	Meter (1σ)

¹From Haque and others (2023b).

The lifetime quarterly mean offsets for Landsat 7 are shown in [figure 85](#). Within the figure, the blue bars indicate the across-track mean offset, and the green bars indicate the along-track mean offset. As of quarter 3 (July–September), 2023, this across-track offset has exceeded 98 meters, with an even greater offset of 128 meters measured in quarter 1, 2023 (Haque and others, 2023a).

The lifetime quarterly geodetic accuracy for Landsat 7 is shown in [figure 86](#). The figure shows the expected geodetic accuracy of a systematic product. Magenta bars indicate the across-track root mean square error (RMSE), and light blue bars indicate the along-track RMSE. As of quarter 3, 2023, this across-track offset has exceeded 77 meters, with an even greater offset of 133 meters measured in quarter 1, 2023 (Haque and others, 2023a). The along-track offset has exceeded 106 meters.

Landsat 7 Band Registration Accuracy

Internal band registration measures how accurately the various Landsat 7 spectral bands are aligned to each other. The assessment provides a numerical evaluation of the accuracy of the band registration within an image using automated cross-correlation techniques between the bands to be assessed (USGS, 2021d).

The per-band average RMSE since launch is shown in [figure 87](#). Blue bars indicate band registration accuracy in the line direction, and green bars indicate band registration accuracy in the sample direction. This figure also shows the specification offsets, which each band easily outperforms.

Landsat 7 Orbital Drift from Worldwide Reference System-2

Landsat 7 is nearing the end of its fuel supply. To conserve fuel, satellite inclination maneuvers have been eliminated, causing the satellite to slowly drift off the nominal WRS–2 orbit. The Cal/Val Team continues to monitor Northern and Southern Hemisphere sites to quantify the amount of WRS–2 displacement. Stakeholders use this information to determine the usability of the data. From April 6 to May 5, 2022, Landsat 7 went through several orbital maneuvers to lower the orbit by 8 kilometers, which has resulted in substantial differences in scene center easting when compared with the displacement before the orbital maneuvers.

The observed orbital drift from WRS–2 for path 39, row 37 (lat 33°10'37" N., long 115°38'05" W.), which is a Northern Hemisphere scene, is shown in [figure 88](#). Magenta diamonds in the figure indicate the scene center location converted to easting and, for historical trending purposes, the

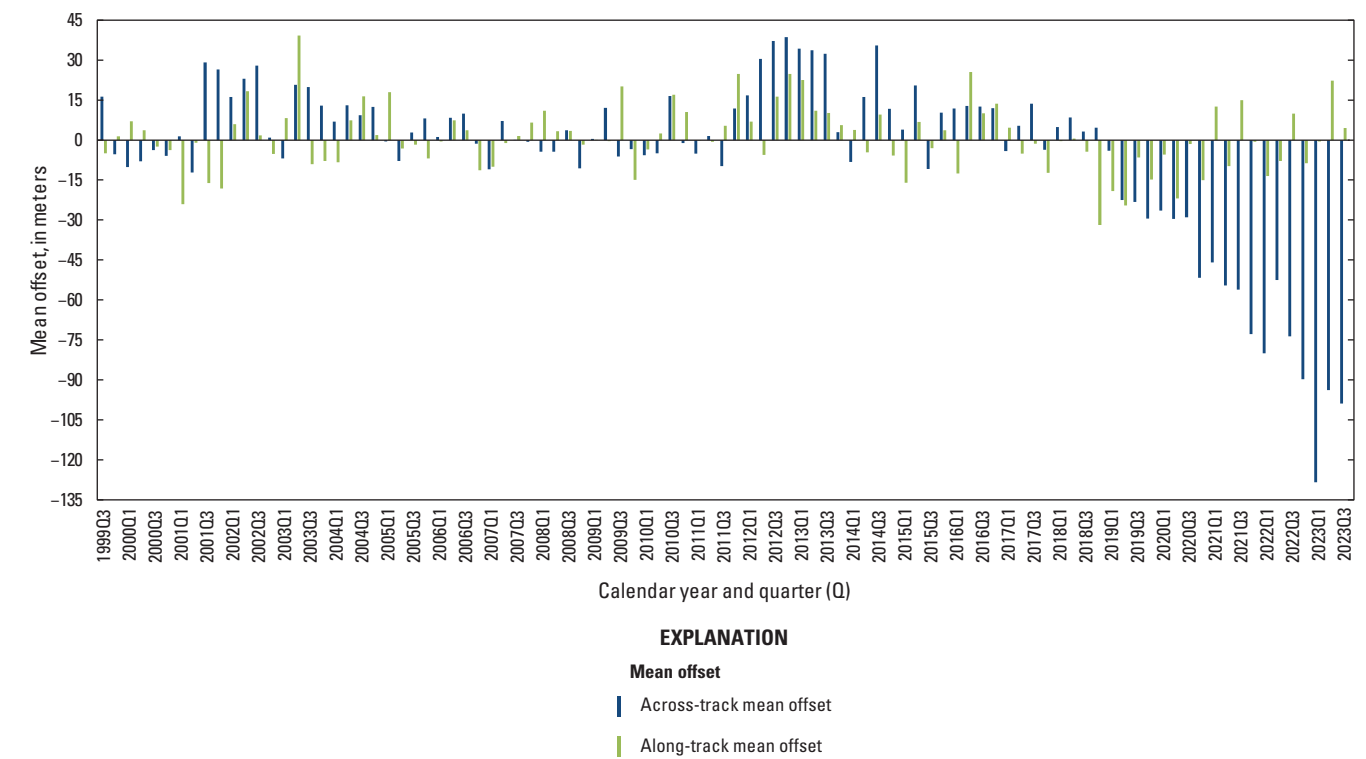


Figure 85. Landsat 7 lifetime mean offsets per quarter.

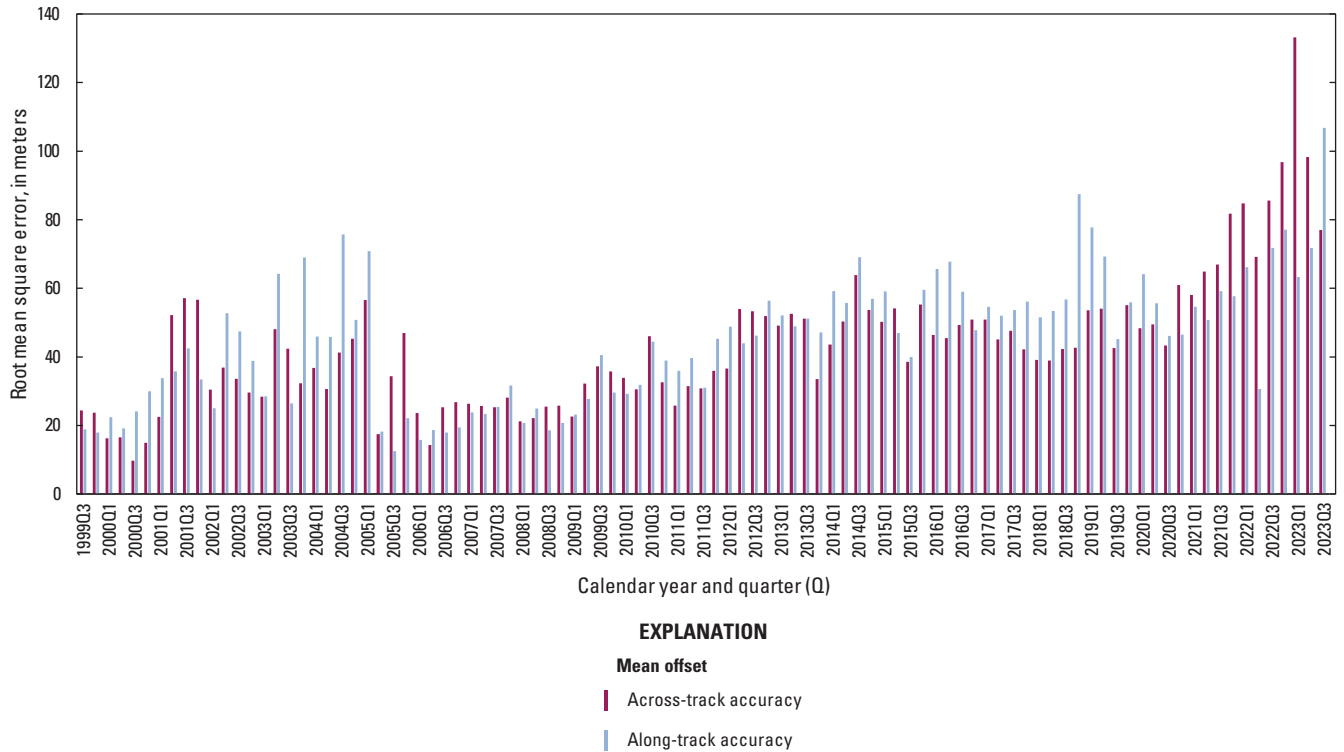


Figure 86. Landsat 7 lifetime geodetic accuracy per quarter.

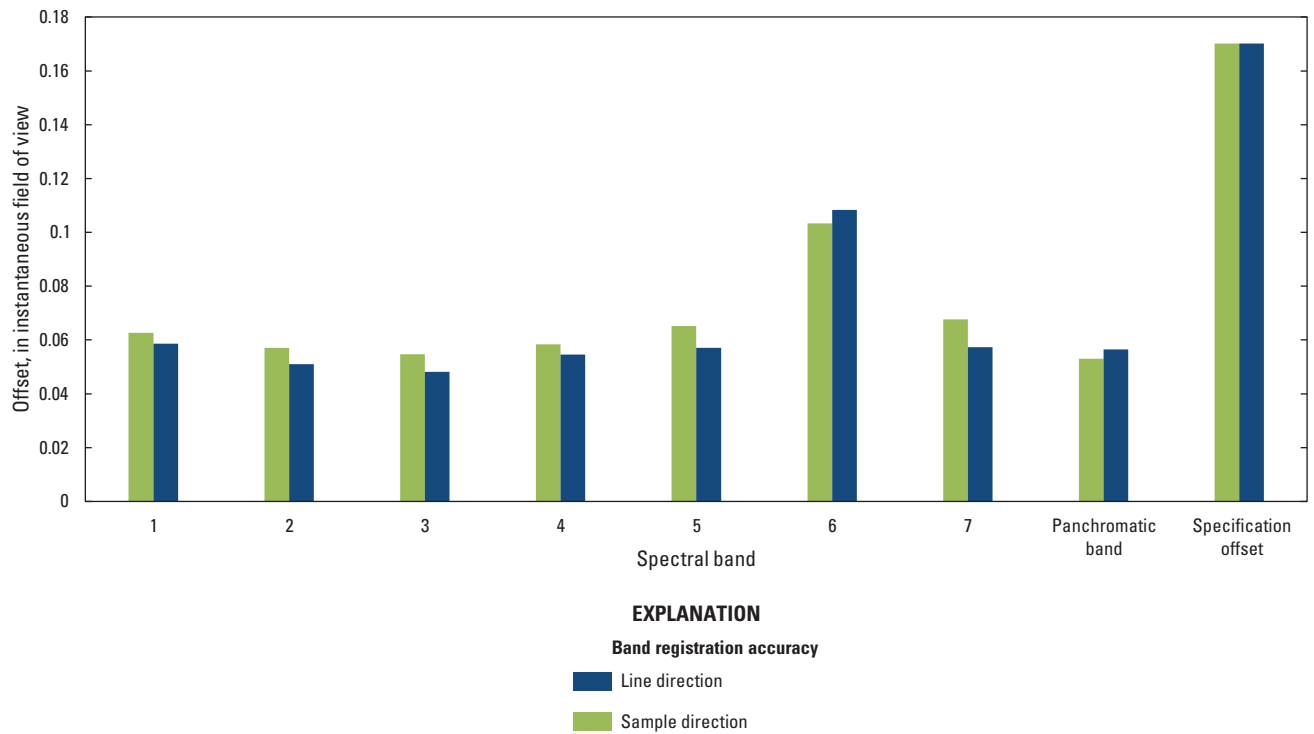


Figure 87. Landsat 7 band-average root mean square registration error since launch.

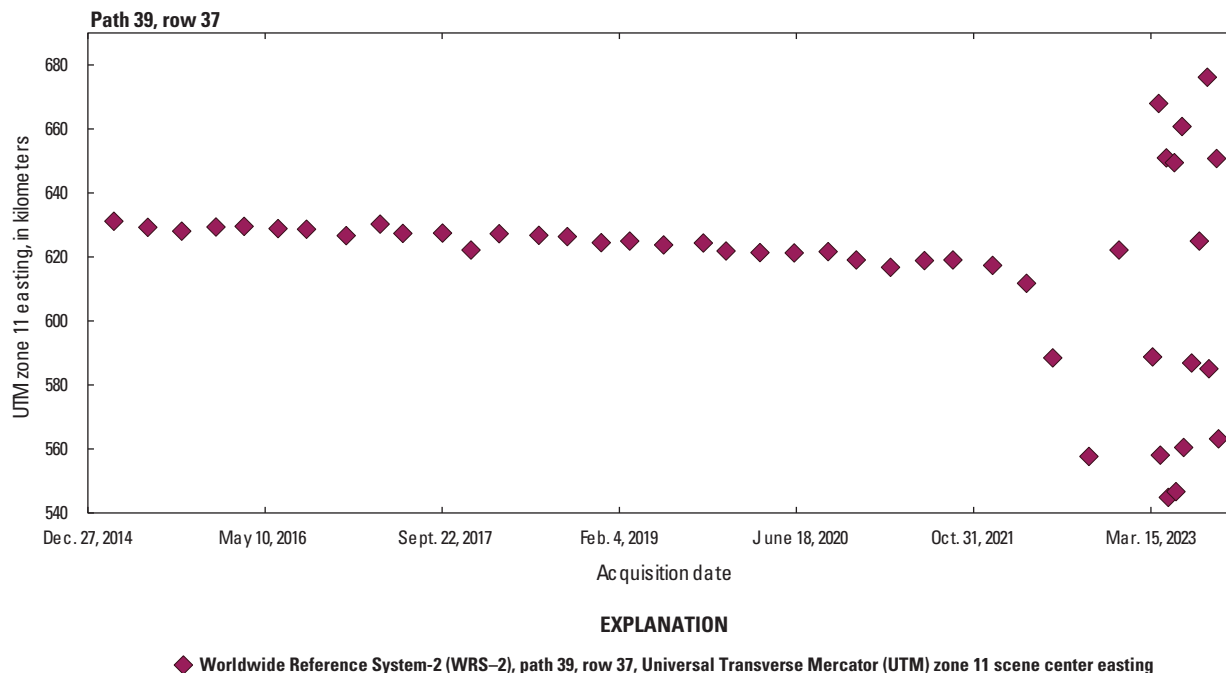


Figure 88. Landsat 7 lifetime orbital drift from World Reference System-2 (path 39, row 37).

measurements begin in 2015. The difference between extreme measurements is about 131.3 kilometers. The drift for this Northern Hemisphere scene was to the west until the orbit-lowering maneuvers, after which substantial westward and eastward drift fluctuations were observed. The most recent observations from September 2023 provide further indication of westward and eastward drift fluctuations.

The observed orbital drift from WRS-2 for path 100, row 73 (lat 18°47'14" S., long 138°22'13" E.), which is a Southern Hemisphere scene, is shown in [figure 89](#). Again,

magenta diamonds indicate the scene center location converted to easting, and the figure has measurements from 2015 to the current quarter. The difference between extreme measurements is about 156.5 kilometers. The drift for this Southern Hemisphere scene was to the east until the orbit-lowering maneuvers, after which substantial westward and eastward drift fluctuations were observed.

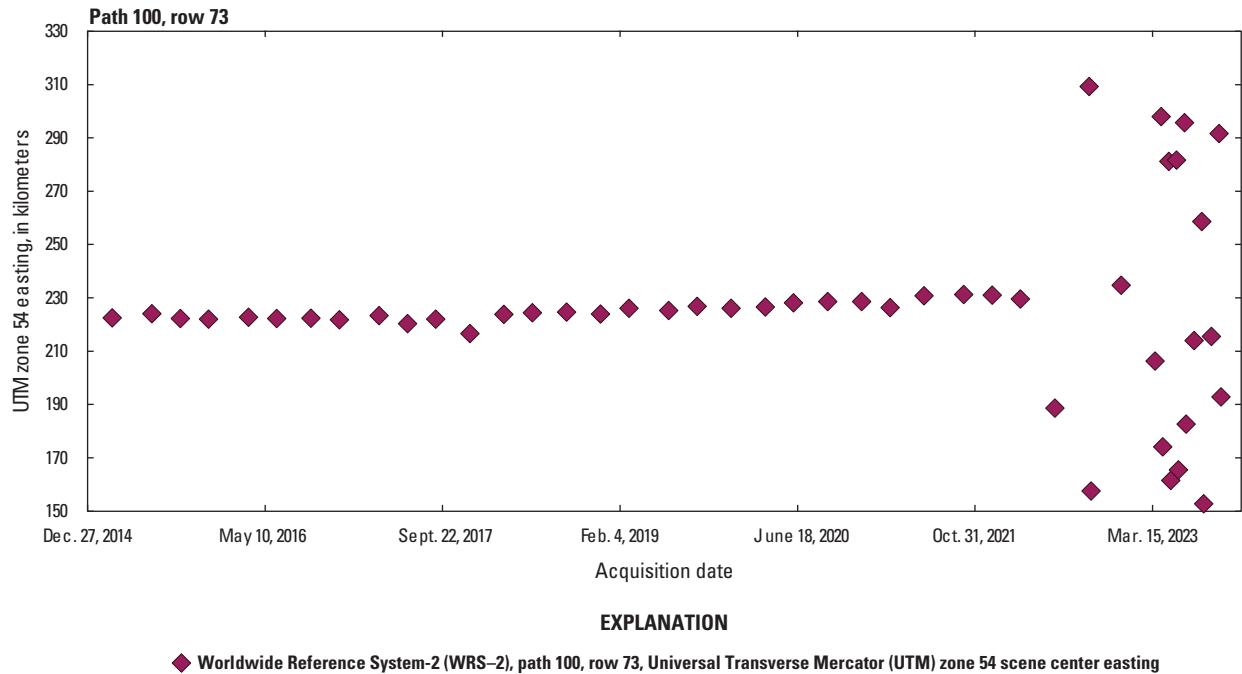


Figure 89. Landsat 7 lifetime orbital drift from World Reference System-2 (path 100, row 73).

Quarterly Level 2 Validation Results

In addition to L1 products, Landsat 7, Landsat 8, and Landsat 9 surface reflectance PICS trending is completed by the Cal/Val Team. The primary purpose of Level 2 surface reflectance PICS trending is to repeatedly characterize the temporal stability of the ETM+ and OLI sensors. The CNES ROI has been chosen for completing the analysis and the results are summarized in this section.

Level 2 Surface Reflectance Pseudoinvariant Calibration Site Trending

The Collection 2, Level 2 lifetime surface reflectance trends for six Landsat 7 spectral bands for the Libya 4 PICS are provided in [figure 90](#). The x-axis represents years since launch, and the y-axis represents surface reflectance. For this analysis, cloud-free data were used. A strong seasonal

effect was noted in the longer wavelength (SWIR) bands (not shown). This seasonal effect has been reduced using appropriate linear models. After reducing seasonality from all bands, drift was estimated for each band from the slope and intercept of line fits. A slight positive drift was noticeable for all bands except for the blue band.

The Collection 2, Level 2 lifetime surface reflectance trends for seven Landsat 8 spectral bands for the Libya 4 PICS are provided in [figure 91](#). Drift estimate results indicate small decay in responsivity for all bands. The x-axis represents years since launch, and the y-axis represents surface reflectance. The seasonal effect has been reduced from all bands using appropriate models. While still very early in the mission, the Collection 2, Level 2 lifetime surface reflectance observations for seven Landsat 9 spectral bands for the Libya 4 PICS are provided in [figure 92](#).

Overall, OLI and ETM+ indicated stability for Level 2 surface reflectance based on the analysis completed. No substantial instability was monitored in any band, according to the lifetime drift estimate results.

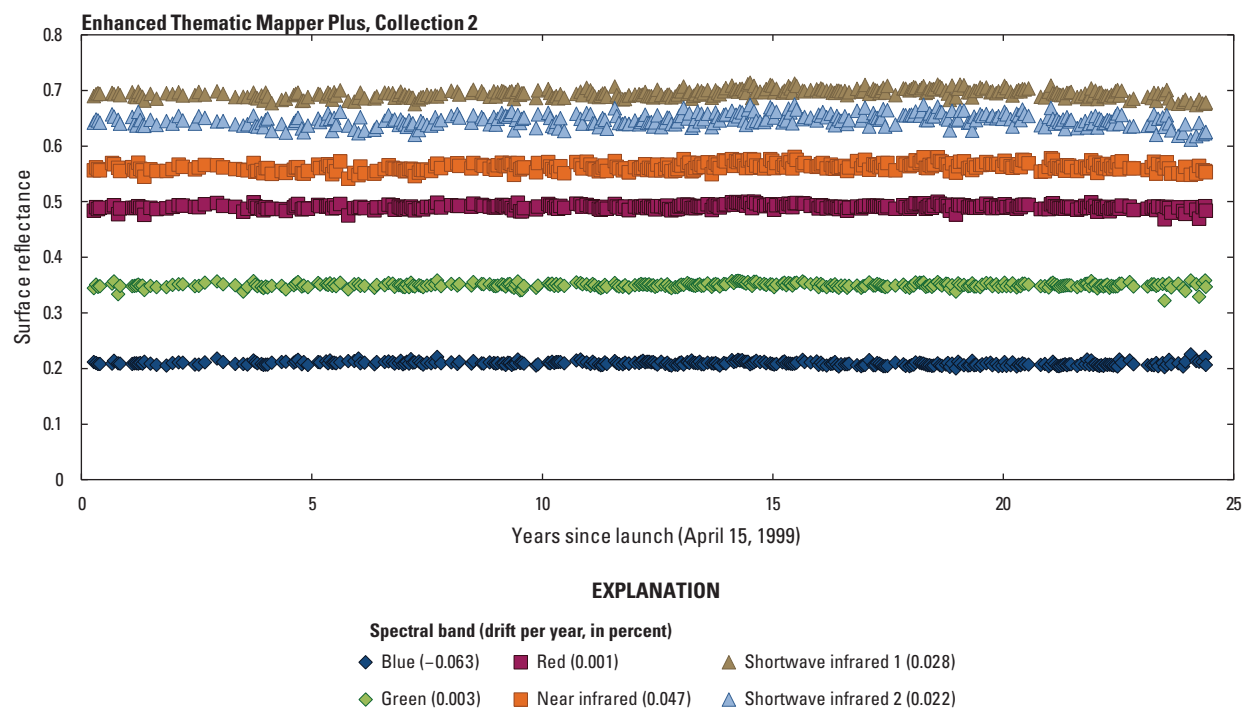


Figure 90. Libya 4 pseudoinvariant calibration site surface reflectance trending, Landsat 7 Enhanced Thematic Mapper Plus, Collection 2.

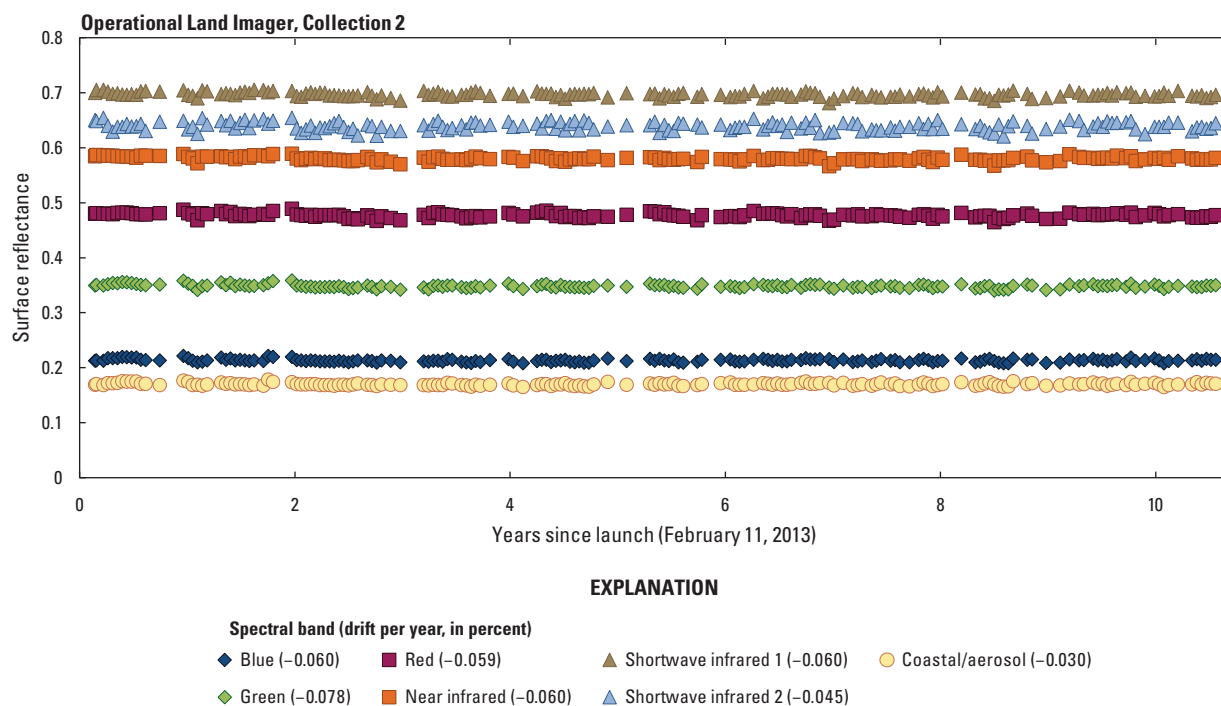


Figure 91. Libya 4 pseudoinvariant calibration site surface reflectance trending, Landsat 8 Operational Land Imager, Collection 2.

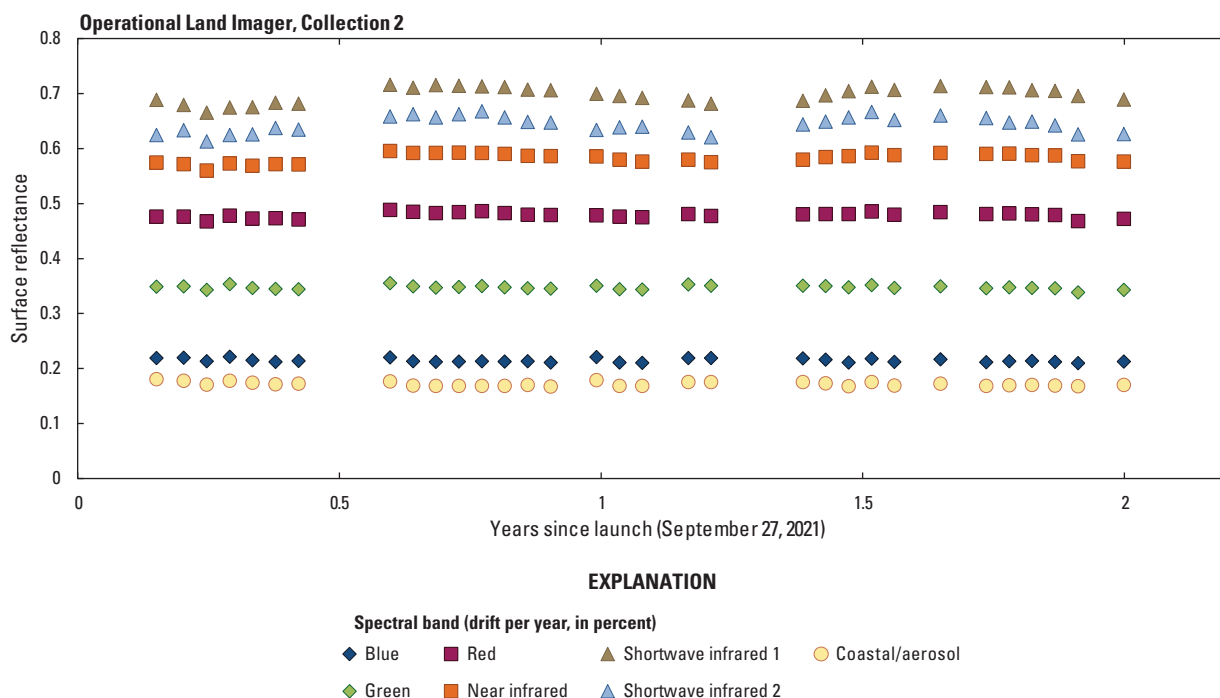


Figure 92. Libya 4 pseudoinvariant calibration site surface reflectance trending, Landsat 9 Operational Land Imager, Collection 2.

Summary

The Landsat 9 and Landsat 8 Operational Land Imager and Thermal Infrared Sensor on-orbit radiometric and geometric performance for quarter 3 (July–September), 2023, meets all requirements. Landsat 7 Enhanced Thematic Mapper Plus (ETM+) on-orbit geometric performance for this reporting quarter meets all requirements. Although not measured against specified requirements, Landsat 7 ETM+ on-orbit radiometric performance was fully characterized and summarized in this report. Additionally, quarterly Level 2 validation results for Operational Land Imager and ETM+ indicated stability for Level 2 surface reflectance.

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